

# South Delta Water Agency's

## Memorandum of Points and Authorities in Support of its Appeal of DWR's “Delta Conveyance Project: Final Certification of Consistency for 2024-2026 Proposed Geotechnical Activities”

### 1. **DWR Cannot Chop the Delta Conveyance Project (“DCP”) into Bite-Sized Pieces and Certify the Pieces in Complete Isolation From the Rest of the Pieces; The Entirety of the DCP Must be Certified in the Same Certification.**

On December 21, 2023, DWR issued a Notice of Determination declaring and informing the public that it approved its so-called “Delta Conveyance Project” (“DCP”). In particular, DWR approved the following:

The Project consists of the construction, operation, and maintenance of new State Water Project (SWP) water diversion and conveyance facilities in the Delta that would be operated in coordination with the existing SWP facilities.

(DCP.A.1.00001.pdf, p. 3.) According to DWR, the construction, operation, and maintenance of the DCP includes several “key components and actions,” including the following:

Efforts to identify geotechnical, hydrogeologic, agronomic, and other field conditions that will guide appropriate construction methods and monitoring programs for final engineering design and construction.

*(Ibid.)*

DWR concedes that the DCP is a “covered action” under the Delta Reform Act. Because the DCP is a covered action, DWR must comply with Water Code section 85225, which provides (with emphasis added):

A state or local public agency that proposes to undertake a covered action, prior to initiating the implementation of that covered action, shall prepare a written certification of consistency with detailed findings as to whether the covered action is consistent with the Delta Plan and shall submit that certification to the council.

Notwithstanding this clear Legislative directive, DWR is proposing to “initiate the implementation” of the above-described “key component and action[]” by only certifying the consistency of a small portion of that “key component and action” in complete isolation of the rest of that component and action and in complete isolation from all other key and other components and actions of the covered action. Such a proposal must be rejected because it is an attempt to entirely and fundamentally circumvent the direct prohibition against the implementation of a covered action in section 85225.

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a. **Section 85225 Prohibits the Implementation of Any Activities of a Covered Action that May Result in Physical Changes to the Delta Environment Prior to Submitting a Written Certification of Consistency for the Entirety of the Covered Action.**

Under the Delta Reform Act, a “covered action” “is a ‘project,’ as defined pursuant to section 21065 of the Public Resources Code. Section 21065 is part of the California Environmental Quality Act (“CEQA”) and provides:

“Project” means an activity which may cause either a direct physical change in the environment, or a reasonably foreseeable indirect physical change in the environment, and which is any of the following: . . . (a) An activity directly undertaken by any public agency. . . .

Because covered actions are by definition comprised of activities that may result in direct or indirect physical changes to the Delta environment, the prohibition against implementing the covered action prior to filing a written certification is intended to prohibit those activities before they are carried out. Like CEQA, a written certification of consistency is not a *post hoc* justification for physical changes that have already taken place. The written certification comes first to ensure the physical changes are consistent with the Delta Plan and will not thwart that plan before they are carried out and cannot be undone.

DWR’s proposed 2024-2026 Geotechnical Activities will undisputedly result in direct and indirect physical changes to the Delta environment and, accordingly, are the precise type of physical activities that section 85225 prohibits in the absence of a certification for the entire covered action.

b. **Section 85225 Prohibits DWR From Extracting Small Pieces of the Covered Action and Certifying Them in Isolation From All Other Pieces of the Covered Action.**

What DWR is proposing is remarkably misplaced and unlawful. DWR presumably thinks it is okay to pick and choose certain activities of the DCP that it believes will be consistent with the Delta Plan and evaluate the consistency of those activities with that plan in complete isolation from all the other activities of the covered action. Such “piecemealing” of a project is a cardinal sin in CEQA. For similar reasons, DWR’s proposed piecemealing of the covered action under the Delta Reform Act is a fundamental and intolerable error.

As noted above, in order to be a covered action the proposed activities must be a project under CEQA. Under CEQA a project cannot, under any circumstances, be chopped up into bite-sized pieces such that the environmental impacts of the pieces are analyzed in complete isolation of all other pieces. Under CEQA “‘[p]roject’ means the whole of an action, which has a potential for resulting in either a direct physical change in the environment, or a reasonably foreseeable indirect physical change in the environment . . . .” (Guidelines, § 15378, subd. (a), emphasis added.) As the court explains in *Orinda Assn v. Board of Supervisors* (1986) 182 Cal.App.3d 1145, at page 1171:

A public agency is not permitted to subdivide a single project into smaller individual sub-projects in order to avoid the responsibility of considering the environmental impact of the project as a whole. "The requirements of CEQA, 'cannot be avoided by chopping up proposed projects into bite-size pieces which, individually considered, might be found to have no significant effect on the environment or to be only ministerial.' [Citation.]" [Citation].

Because a covered action "is a 'project,' as defined pursuant to section 21065 of the Public Resources Code" (i.e. pursuant to CEQA), a covered action also means "**the whole of an action**, which has a potential for resulting in either a direct physical change in the environment, or a reasonably foreseeable indirect physical change in the environment . . . ." (Guidelines, § 15378, subd. (a), emphasis added.) Accordingly, DWR cannot avoid considering the consistency of the DCP as a whole with the Delta Plan by chopping the DCP into bite-sized pieces, which, individually considered, might be deemed consistent with the Delta Plan.

When piecemealing contentions arise in CEQA, the debate is whether one piece of an activity is part of the same project as another activity. Here, DWR concedes in its Notice of Determination that the proposed geotechnical activities are a "key component and action" of the DCP. (DCP.A.1.00001.pdf, p. 3.) Hence, here, the piecemealing is particularly egregious because there is no debate that DWR is improperly separating those activities from all other activities of the DCP.

The instant piecemealing is also particularly egregious because of the staggering amount of layers of piecemealing. Here, DWR chopped up the DCP in at least the following manners:

- DWR separated the construction component of the DCP from the operation and maintenance components.
- DWR then separated the field investigations from all other components of the construction component.
- DWR then separated the pre-construction field investigations from the post-construction field investigations.
- DWR then separated the geotechnical investigations from all other components of the pre-construction field investigations.
- DWR then separated borings, CPTs, and water sampling geotechnical investigations from all other geotechnical investigations.
- DWR then separated land-based borings and CPTs from overwater borings and CPTs.
- DWR then separated certain land-based borings and CPTs from other land-based borings and CPTs (e.g., based on their proximity to levees and other factors).

After at least these seven subdivisions of the DCP, DWR then prepared the instant certification contending the remaining bite-sized piece of the DCP is consistent with the Delta Plan. It is frankly bewildering how DWR could have done this with a straight face. In no way, shape, or form can this be tolerated under the Delta Reform Act. Because a covered action is a project under CEQA, the DCP cannot be chopped up into two (2) pieces to evade the prohibition against implementing the DCP in Water Code section 85225, much less chopped up into seven (7) or more pieces.

It is manifest and commonsense that all components and actions of a covered action must be certified together. If a project proponent could subdivide a covered action into as many bite-sized pieces as it desired, there would never be an assessment of the cumulative effect from all of the pieces of the covered action together on the co-equal coals and the Delta Plan's policies. That would constitute the ultimate circumvention of section 85225 and the principles and purposes of the Delta Reform Act, including the following:

“It is the intent of the Legislature that state and local land use actions identified as “covered actions” pursuant to Section 85057.5 be consistent with the Delta Plan. . . .” (Wat. Code, § 85022.)

The subdivision of a covered action into pieces directly thwarts the Legislature's intent that covered actions be consistent with the Delta Plan. If subdivisions are tolerated, only parts of the covered action could be deemed consistent with the Delta Plan. There would be no certification that the covered action as a whole is consistent with the Delta Plan.

Moreover, the entire purpose of the Delta Plan is to “guid[e] state and local agency actions related to the Delta.” (Wat. Code, § 85300.) That guidance is fundamentally thwarted if covered actions are subdivided and individual pieces are certified in complete isolation from all other pieces.

For these reasons, DWR's attempted subdivisions of certain geotechnical activities from the totality of geotechnical activities and other activities that comprise the DCP is intolerable under the Delta Reform Act. Such attempt must be denied on the grounds that DWR's certification is defective for failure to include the “whole of the action” that comprises the covered action. The certification should also be denied on the grounds that there is a gross and complete lack of substantial evidence in the record that the DCP as a whole is consistent with the Delta Plan.

**c. A Pending Court Case Has Already Determined that DWR Cannot Separate the Geotechnical Activities from the DCP for Purposes of Certification.**

In its certification package, DWR includes a copy of the “Ruling on Submitted Matter–Petitioners' Motions for Preliminary Injunction,” in *Tulare Lake Basin Water Storage District v. CA Department of Water Resources*, Case No. 24WM000006 et al. In that ruling the Court addressed this precise issue and held:

The Department defined the DCP to include the geotechnical work at issue here. The FEIR analyzed the geotechnical work as part of the project (Baykeeper RJN,



Ex. A, pp. 3-2, 3-134 to 3-141), and the Notice of Determination described it as a “key component” of the project (*Id.*, Ex. B, Attachment 2). Because the geotechnical work is part of the “project” within the meaning of CEQA, it is necessarily part of a “covered action” within the meaning of Water Code section 85225.

(DCP.X2.1.00020, at “PDF” p. 117.) The Court further held:

The motions for preliminary injunction are granted. The geotechnical work at issue here is part of the covered action [i.e., the DCP], which requires certification of consistency with the Delta Plan before it is implemented. The Department is, therefore, enjoined from undertaking the geotechnical work described in Chapter 3 of the FEIR prior to completion of the certification procedure that the Delta Reform Act requires.

(*Id.*, at “PDF” pp. 124-125.)

Notwithstanding that clear directive, DWR is burdening stakeholders and the DSC and its staff with a certification of consistency that is directly prohibited by that Court ruling.

- d. **If DWR Wants to Begin Implementing the Geotechnical Investigation Component of the DCP, then DWR Must Certify the Entirety of the DCP; If DWR Thereafter Wants to Substantially Change the DCP as a Result of those Investigations, then DWR Can and Must File a Supplemental Certification to Address those Changes.**

DWR has been studying the DCP for many years and determined on December 21, 2023 that it had enough information to approve the construction, operation, and maintenance of the DCP. If DWR wants to begin implementing any component of the DCP, including the geotechnical investigation component, then DWR must file a certification for the entirety of the DCP that it approved on December 21, 2023.

DWR made various engineering and design assumptions when it approved its Final EIR for the DCP. DWR can make reasonable engineering and design assumptions in its certification. If the completion of the proposed geotechnical activities, or any other geotechnical or field investigations, provides DWR with a reason to propose substantial changes to the design or other aspects of the DCP, then DWR can and should file a supplemental certification to address those changes. The Delta Reform Act readily accommodates such supplemental certifications and DWR can and should utilize them as necessary to address any proposed significant changes to the DCP that DWR desires to implement after its initial certification of the DCP.

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2. **Inconsistency with the Delta Plan.**

a. **Because DWR Failed to Certify the “Whole of the Action” that Comprises the DCP, there Is No Substantial Evidence in the Record to Support a Finding that the Entirety of the DCP is Consistent with the Delta Plan.**

As discussed above, DWR’s attempt to certify only a small portion of the activities that comprise the covered action (the DCP) in complete isolation from all the other activities that comprise the DCP is unlawful and must be denied as a matter of law. The failure to certify the “whole of the action” that comprises the DCP also results in a complete failure on DWR’s part to provide substantial evidence in the record that the entirety of the DCP is consistent with the Delta Plan and all of its regulatory policies. Accordingly, DWR’s certification must also be denied on the grounds that the record does not contain such evidence. (See Wat. Code, § 85225.25 [the certification must be “supported by substantial evidence in the record before the state or local public agency that filed the certification”].)

b. **The Geotechnical Activities are Inconsistent with Policy “G P1–Detailed Findings to Establish Consistency with the Delta Plan” (Cal. Code Regs., tit. 23, § 5002).**

California Code of Regulations, title 23, section 5002, provides:

(b) Certifications of consistency must include detailed findings that address each of the following requirements:

(1) Covered actions, in order to be consistent with the Delta Plan, must be consistent with this regulatory policy and with each of the regulatory policies contained in Article 3 implicated by the covered action. . . ;

(2) Covered actions not exempt from CEQA must include all applicable feasible mitigation measures adopted and incorporated into the Delta Plan as amended April 26, 2018, which is here by incorporated by reference, (unless the measure(s) are within the exclusive jurisdiction of an agency other than the agency that files the certification of consistency), or substitute mitigation measures that the agency that files the certification of consistency finds are equally or more effective;

(3) As relevant to the purpose and nature of the project, all covered actions must document use of best available science; . . .

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i. **DWR Fails to Adopt All Applicable or Substitute Feasible Mitigation Measures and Fails to Use Best Available Science to Address Impacts from Improperly Sealed Boring and CPT Holes.**

Regarding mitigation of impacts from the Geotechnical Activities, DWR repeatedly relies on the “sealing” of the boring and CPT holes after the work is completed to support its conclusions that there will be no impacts from such holes and, hence, no mitigation is required. For example, regarding the Delta Plan impact, “Violate Any Water Quality Standards or Waste Discharge Requirements or Substantially Degrade Water Quality,” DWR states the following:

[W]hen completed, holes will be sealed using cement-bentonite grout in accordance with State of California regulations and industry standards to ensure that groundwater water quality will not be contaminated by the borings in a way that would cause surface water quality to be substantially degraded. Therefore, impacts to the specific constituents evaluated in the Final EIR water quality impacts analysis will not occur and no mitigation is required.

(DCP.X2.1.00020, at “PDF” p. 50, emphasis added.)

DWR makes similar statements regarding potential impacts to other resources, including the following:

- Delta Plan Impact: Substantially Deplete Groundwater Supplies or Interfere Substantially with Groundwater Recharge. (*Id.*, “PDF” p. 51.)
- Delta Plan Impact: Create or Contribute Runoff Water which would Exceed the Capacity of Existing or Planned Stormwater Drainage Systems or Provide Substantial Additional Sources of Polluted Runoff. (*Id.*, “PDF” p. 61.)
- Delta Plan Impact: Conversion of Farmland to Nonagricultural Use. (*Id.*, “PDF” p. 65.)
- Delta Plan Impact: Conflict with Existing Zoning for Agricultural Use or a Williamson Act Contract. (*Id.*, “PDF” p. 66.)

There is a lack of substantial evidence to support DWR’s determination that the alleged “sealing” of the boring and CPT holes will avoid such impacts and a lack of substantial evidence that DWR is using the best available science to address improper sealing of those holes.

(1) **It is Well-Established that Improperly Sealed Boring or CPTs Holes Can Adversely Impact Levee Integrity.**

Improperly sealed boring or CPT holes can result in preferential paths for seepage to flow from the nearby rivers through or under the levees and through the improperly sealed holes. Attached hereto as **Exhibit “A”** is the “Analytical Study on Flood Induced Seepage Under River Levees,” which explains the hydrostatic pressure that creates seepage (at p. 14):

“Whenever a levee is subjected to a differential hydrostatic head of water as a result of river stages higher than the surrounding land, seepage enters the pervious substratum through the bed of the river and riverside borrow pits or the riverside top stratum or both, and creates an artesian head and hydraulic gradient in the sand stratum under the levee. This gradient causes a flow of seepage beneath the levee and the development of excess pressures landward thereof. If the hydrostatic pressure in the pervious substratum landward of the levee becomes greater than the submerged weight of the top stratum, the excess pressure will cause heaving of the top blanket, or will cause it to rupture at one or more weak spots with a resulting concentration of seepage flow in the form of sand boils.

“In nature, seepage usually concentrates along the landside toe of the levee, at thin or weak spots in the top stratum, and adjacent to clay-filled swales or channels. Where seepage is concentrated to the extent that turbulent flow is created, the flow will cause erosion in the top stratum and development of a channel down into the underlying silts and fine sands, which frequently exist immediately beneath the top stratum. As the channel increases in size or length, or both, a progressively greater concentration of seepage flows into it with a consequent greater tendency for erosion to progress beneath the levee.

“The amount of seepage and uplift hydrostatic pressure that may develop landward of a levee is related to the river stage, location of seepage entrance, thickness and perviousness of the substratum and of the landside top stratum, underground storage, and geological features. Other factors contributing to the activity of the sand boils caused by seepage and hydrostatic pressure are the degree of seepage concentration and the velocity of flow emerging from the boils.”

See also the following:

- Corps’ ER 1110-1-1807, entitled “Engineering and Design, Drilling in Earth Embankment Dams and Levees” (attached hereto as **Exhibit “B”**), which discusses, among other impacts, the potential for drilling on or near levees to create preferential seepage paths.
- January 13, 2020 Memorandum prepared by Gilbert Cosio, Jr., an Engineer with MBK Engineers (attached hereto as **Exhibit “C”**), which discusses concerns with improperly sealed borings.
- Several photos of boils that have erupted from preferential seepage paths (attached hereto as **Exhibit “D”**).

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**(2) It is Also Well-Established that Improperly Sealed Boring or CPTs Holes Can Adversely Impact Groundwater Quality and Surface Water Quality.**

Attached hereto as **Exhibit “E”** is a copy of Chapter 11—“Cone Penetrometer” from the USDA/NRCS’ “Part 631 Geology National Engineering Handbook.” At page 11-12, it discusses the challenges with properly sealing CPT holes:

**(d) Hole closure—techniques.** The need for grouting or sealing of holes is usually established by individual States, most of which have laws requiring that exploration holes be backfilled, sealed, or grouted after sampling and testing are completed. The same applies to CPT sounding holes. This is of particular importance in specific geologic settings where aquifer(s) need to be protected against crosscontamination or water transmission.

As the CPT cone is pushed into the ground, it is creating a hole that could be as detrimental to groundwater as an open borehole. If the hole stays open after the tool is withdrawn, these cavities can become pathways for contamination of aquifers either by cross-communication between permeable units or by the transport of surface contaminants down the hole. Surface and subsurface contaminants can potentially flow into aquifers that were previously uncontaminated.

Providing a permanent seal in small diameter holes presents a number of challenges compared with large diameter holes drilled with a conventional drill rig. In larger-diameter holes, successful sealing can be performed using bentonite. In smaller diameter holes, it can be difficult or impossible to verify the seal’s effectiveness due to the likelihood of bridging.

Specific geologic conditions may cause the holes to immediately close as the tool is removed. The best examples are relatively clean sands below the water table and very soft, saturated clays. Borings in relatively clean, saturated sands are well known for unstable sidewalls that collapse during the drilling process. Drilling mud must be used to counteract this instability to keep the hole open. In loose deposits, the vibrations from the cone truck are enough to cause collapse during retraction. At the same time, the hydraulic conductivity in these deposits is likely to be several orders of magnitude above that of the sealing materials. For very soft clays below the water table, the hole may squeeze shut as the tools are being withdrawn. Suction that develops as the penetrometer is pulled from the hole increases this action.

**(3) There is No Substantial Evidence in the Record to Verify the Success of DWR’s Sealing of Boring and CPT Holes.**

Despite the fact that DWR acknowledges the importance of properly sealing the boring and CPT holes and relies on that sealing to mitigate impacts from improperly sealed borings, there is no evidence in the record to attest to the success of DWR’s sealing of the holes. As just

noted above, the USDA explains that for smaller diameter holes like CPTs, “it can be difficult or impossible to verify the seal's effectiveness due to the likelihood of bridging.” Nevertheless, there are at least three ways DWR could and should provide evidence that the prior hundreds of boring and CPT holes for the DCP and its variants have been properly sealed:

- (1) DWR could confirm through its drilling and CPT logs how often it is able to grout the entire length of the boring or CPT hole. For example, if it created a 200 foot hole, was it able to insert the grout pipe (i.e., the “tremie pipe”) all the way to the bottom of that 200 foot hole, or did it lose the hole or the did the other otherwise cave in such that the grout pipe could not make it to the bottom? This information should be readily available from its work logs.
- (2) DWR’s Bulletin 74-90–“California Well Standards” (attached hereto as **Exhibit “F”**) which DWR indicates it complies with (see e.g., DCP.X2.1.00020, at “PDF” p. 227), states: “Verification. It shall be verified that the volume of sealing material placed at least equals or exceeds the volume to be be sealed.” (Bulletin 7-90, p. 22, emphasis added.) DWR could also easily compile this information and enter it into the record.
- (3) DWR could explain how often, if ever, it inspects the boring and CPTs sites after it “seals” them to ensure there has been no observable settlement of the grout within the hole (which among other things could expose the groundwater to surface contaminants that enter the hole) or observable seepage flowing out of it. If it does inspect them, how often does it observe settlement or seepage and, if it observes settlement or seepage, what does it do about it. This, again, is information that should be readily available and easy to compile, if it is not already compiled.

As it stands, there is no evidence in the record to verify the success of DWR’s sealing of hundreds of prior boring and CPT holes and, accordingly, no reason to believe they have all been properly sealed through the entirety of the holes and without incident. The recent substantial seepage flow through or under the Victoria Island levee that has been in the news lately and that is currently threatening to fail the levee is all the more reason to take additional precautions to ensure the prior hundreds of boring and CPTs holes and the proposed additional hundreds of boring and CPTs holes are not causing or contributing to increased seepage flow through or under levees. Activities that threaten the integrity of the Delta’s vast network of essential levees constitute a manifest “significant adverse impact on the achievement of one or both of the coequal goals [and] implementation of government-sponsored flood control programs to reduce risks to people and property in the Delta . . . .” (Wat. Code, § 85225.10, subd. (a).)

With DWR proposing to perform 261 borings and up to 15 CPTs over the next two years, it is imperative that DWR provide substantial evidence confirming the efficacy of its sealing protocol in the unique and varied Delta soil conditions. Moreover, use of the best available science would at a minimum call for obtaining, reviewing, disclosing, and documenting the above-requested info. (See Cal. Code Regs., tit. 23, section 5002, subd. (b)(3) [“As relevant to the purpose and nature of the project, all covered actions must document use of best available science”].)

c. **Inconsistency with Policy “ER P5–Avoid Introductions of and Habitat Improvements for Invasive Nonnative Species” (Cal. Code Regs., tit. 23, § 5009).**

California Code of Regulations, title 23, section 5009, provides:

(a) The potential for new introductions of or improved habitat conditions for nonnative invasive species, striped bass, or bass must be fully considered and avoided or mitigated in a way that appropriately protects the ecosystem.

(b) For purposes of Water Code section 85057.5(a)(3) and section 5001(k)(1)(E) of this Chapter, this policy covers a proposed action that has the reasonable probability of introducing or improving habitat conditions for nonnative invasive species.

DWR states that “all equipment used during field investigations [will] be cleaned and inspected by the qualified biologist for terrestrial invasive plant and animal species prior to entering the work areas and before moving between work areas (California Department of Water Resources 2023a:3B-29).” (DCP.X2.1.00020, p. 4-11, emphasis added.) DWR does not specify whether all vehicles will be so cleaned and inspected nor the clothing and footwear of personnel, both of which could reasonably result in the introduction of nonnative invasive species.

d. **Inconsistency with Policy “DP P2–Respect Local Land Use when Siting Water or Flood Facilities or Restoring Habitats” (Cal. Code Regs., tit. 23, § 5011).**

California Code of Regulations, title 23, section 5011, provides:

(a) Water management facilities, ecosystem restoration, and flood management infrastructure must be sited to avoid or reduce conflicts with existing uses or those uses described or depicted in city and county general plans for their jurisdictions or spheres of influence when feasible, considering comments from local agencies and the Delta Protection Commission. Plans for ecosystem restoration must consider sites on existing public lands, when feasible and consistent with a project's purpose, before privately owned sites are purchased. Measures to mitigate conflicts with adjacent uses may include, but are not limited to, buffers to prevent adverse effects on adjacent farmland.

(b) For purposes of Water Code section 85057.5(a)(3) and section 5001(k)(1)(E) of this Chapter, this policy covers proposed actions that involve the siting of water management facilities, ecosystem restoration, and flood management infrastructure.

One of the purported purposes of the Geotechnical Activities is to investigate and confirm the suitability of sites for the DCP’s facilities. Hence, the locations of the Geotechnical Activities are a substantial factor in the ultimate siting of those facilities and will play an instrumental role in that siting. There is no discussion of respecting local land use when siting

those activities and, hence, those facilities. Accordingly, there is no substantial evidence to support the consistency of the Geotechnical Activities with this policy.

**3. Additional Comments re Adverse Impacts on Levees and Property Damage.**

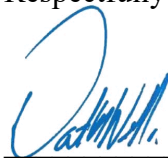
DWR states: “In particular, the 2024–2026 Proposed Geotechnical Activities will not include the following: work on levees, . . . .” (DCP.X2.1.00020, at "PDF" p. 24.) A review of DWR’s maps plainly indicates numerous borings on the landside levee slopes or immediately adjacent to those slopes. As discussed above, such close proximity to the levees raises heightened seepage concerns among other concerns (e.g., interference with flood fighting activities, levee patrols and levee slope visibility).

As DWR is aware, in the court-ordered entry petition proceedings there has been a longstanding “wet season” prohibition against any borings or CPTs from December 1st through April 30th. Seepage concerns are heightened during the wet season when hydrostatic pressure is the highest and levees are heavily saturated by high water and rainfall and damage to landowners’ property and roadways from rutting are virtually inevitable. DWR should add such a restriction to the proposed geotechnical investigations. It has proven to be a feasible and beneficial condition that has successfully avoided seepage and other flood control concerns as well as property damage.

**4. Conclusion.**

For the foregoing reasons, the DSC must reject DWR’s certification of the Geotechnical Activities as a matter of law because it has impermissibly piecemealed the DCP and is directly contrary to a Court order. The DSC should also reject the certification because DWR has failed to provide substantial evidence that those activities by themselves, and joined with all other activities of the DCP, are consistent with the Delta Plan.

Respectfully submitted,



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Attorney for the  
South Delta Water Agency



# Exhibit A

**ANALYTICAL STUDY ON FLOOD INDUCED SEEPAGE  
UNDER RIVER LEVEES**

A Dissertation

Submitted to Graduate Faculty of the  
Louisiana State University and  
Agricultural and Mechanical College  
in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy

in

The Department of Civil and Environmental Engineering

by

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M.S., Louisiana State University, 1996

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## **ABSTRACT**

A common and potentially dangerous phenomenon associated with flooding is seepage under levees and the formation of sand boils. Seepage flow due to hydrostatic head gradients of floods may cause deformation of pervious layers leading to heave, piping and sand boils. Underseepage may also cause irreversible changes in the characteristics of the porous medium. A series of independent flood events may have cumulative effects on pervious layers causing sand boils to grow. Current underseepage analyses for levees are based on steady-state flow. Transient seepage flow due to rapid changes in river head may contribute to cumulative effects and cause critical hydraulic head development under levees and subsequent sand boil formation.

This research examined transient effects on hydraulic head development under levees during a flood event. While the research is focused on levees, this study is applicable to any hydraulic structures (e.g., flood walls, dams, and retaining structures) subject to underseepage. An analytical model was developed for one-dimensional transient flow in a confined aquifer under a levee in response to river stage fluctuations. This analytical model was revised by considering leakage out of confined aquifers to simulate the occurrence of sand boils on the landside of levees. Transient flow nets were also constructed using complex variables. The performance of these analytical models was evaluated by comparing with the limited field studies, current U.S. Army Corps of Engineers underseepage analysis methodology for levees, and a finite element program. The effects of possible cumulative deformations on development of exit hydraulic gradients were also evaluated and discussed.

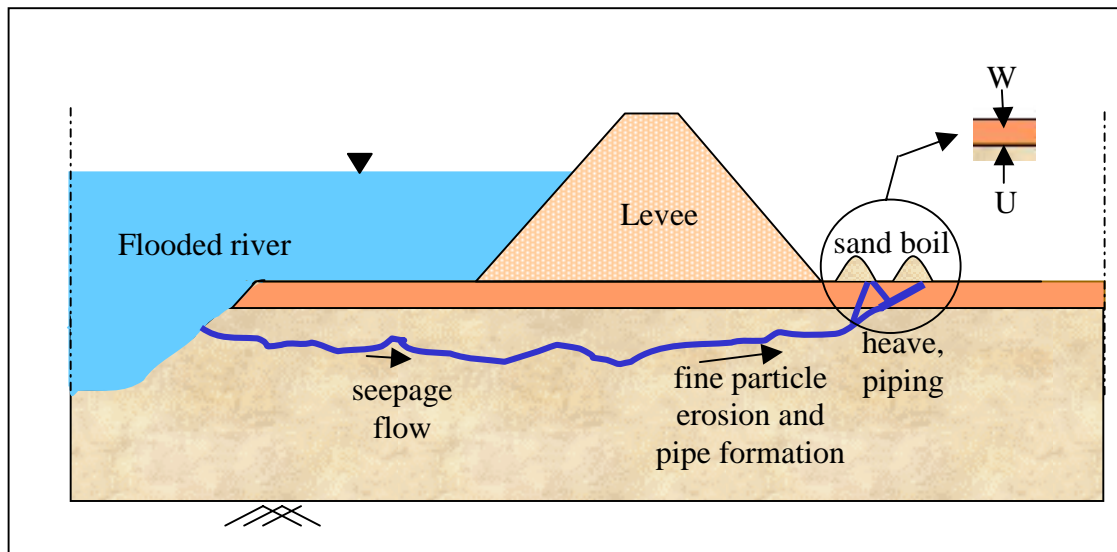
Transient flow models performed reasonably well compared with the limited field studies, the Army Corps seepage analysis method and SEEP2D finite element program.

Cumulative analysis of underseepage by the transient flow model simulating sand boil formations showed significant increases in exit hydraulic gradients in response to possible cumulative changes in aquifer characteristics.

## **CHAPTER 1     INTRODUCTION**

Underseepage of water through soil below levees during times of flood is a natural phenomenon. Seepage becomes a matter of concern for the safety of a levee when piping occurs and sand boils form. Turnbull and Mansur (1961) summarized the flood induced seepage problem under levees based on their experience with the U.S. Army Corps of Engineers (USACE). If the hydrostatic pressure force in the pervious substratum landward of the levee becomes greater than the submerged weight of the overlying strata, the excess pressure may cause heaving of the upper soil layers and rupture at weak spots with a resulting concentration of seepage flow. Flow from these weakened locations may increase to form sand boils. In addition, the concentrated seepage flow may erode fine soil particles, and carry these fine particles up to the surface. As the erosion process continues, a pipe or open channel may form through the top stratum. The pipe-shaped opening through which water and eroded soil discharge is called a sand boil. A sand boil opening bears some resemblance to a soil-walled pipe through the top stratum. The flowing water exiting through a sand boil carries soil particles that have been eroded from along the water's seepage path up to the soil surface where it may deposit to form a cone around the sand boil. Heave and piping are the main mechanisms involved in creating a pipe that leads to sand boils. Heaving occurs when seepage forces push the substrata upward. Piping is the phenomenon where seeping water progressively erodes and washes away soil particles, leaving large voids in the soil. Removal of soil through sand boils by piping or internal erosion damages levees, their foundations, or both, which may result in settlement and has the potential to cause catastrophic failures of levees. A schematic view of the underseepage problem is shown in Fig. 1.1.





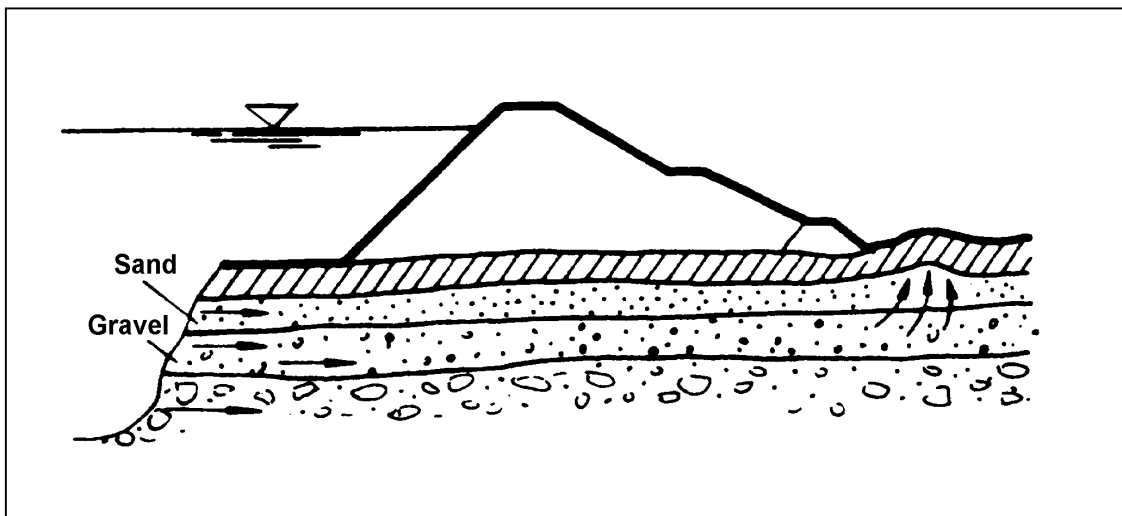
**Fig. 1.1 A schematic representation of seepage problem under levees (U: hydrostatic uplift pressures, W: submerged weight of soil).**

Although an exit hydraulic gradient of 0.85 on the landside of a levee is commonly considered sufficient to initiate sand boil formation, other field measurements show that sand boils may occur with exit hydraulic gradients in the range of 0.54 -1.02 (Daniel, 1985). A photo of a sand boil is shown in Fig. 1.2

While most analyses of underseepage, piping, heaving, and sand boil formation have been based on steady seepage flow, it is unsteady seepage flow that is more common for canal embankments and levees (Peter, 1982). This is because during floods the water level in the river and between the levees changes so quickly that a constant flow regime is unlikely to be established. Instead, rapid changes of water level may cause a head wave moving with varying velocity in the stratified porous medium. Consider that a levee is underlain with a layer of high hydraulic conductivity soil, which extends a distance on the landside of the levee, while a layer of low hydraulic conductivity soil overlies the high conductivity layer on the landside of the levee (Fig. 1.3).



**Fig. 1.2** A picture of a sand boil (source: USACE, Vicksburg District).



**Fig 1.3**A hydraulic structure and seepage forces acting on sand and gravel layer in its subsoil (after Peter, 1982).

When a flood wave occurs in the layer of greater hydraulic conductivity, the head wave reaches farther in a given time than it does in the top layer. As the head wave develops, so do uplift pressures that may induce heave and gradual liquefaction of the overlying

layer. Static liquefaction is a soil state at which vertical effective stress on soil becomes zero (Fig. 1.1). A mass of sand in a state of static liquefaction is known as quicksand, which has lost its strength and behaves like viscous liquid (Budhu, 2000).

If the same problem were to be analyzed as a steady state problem, then the upper layer would be assumed to be wet and thus heavier than similar dry material, so the heave would have been less likely to occur. However, steady seepage is frequently assumed in analyses of levees because the computations are simpler and the steady-state seepage parameters are less difficult to determine than the corresponding transient parameters (Peter, 1982). For these reasons, seepage flow based on transient effects due to changes in river head has not been analyzed in as much detail as has steady flow.

At one time, it was thought that sand boils could “heal” or “repair” themselves between flood events (Sills, G., personal communication to CE 7265 class, Fall 1997). After the 1993 floods on the Upper Mississippi River, some engineers with the U.S. Army Corps of Engineers began to question the extent of the inter-flood healing effect and whether there is a cumulative effect caused by sand boils. (Sills, G., personal communication to CE 7265 class, Fall 1997).

A more recent concept is that seepage under levees during a series of independent flood events may cause sand boils to grow as the flood series grows longer. Researchers have not examined the concept that there may be cumulative effects from sand boils, which increase the likelihood of levee failure due to seepage. As a result, the problem of levee failure due to cumulative effects of underseepage is only now being recognized as a problem that may have great urgency for evaluating the danger to lives and property in areas protected by levee systems. Currently, the USACE Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, is working on research on the

cumulative effects of piping under levees (Wolff, 2002). The research unit operates under the Innovative Flood Damage Research Program (IFDR) sponsored by USACE.

## **1.1 Objectives**

The objective of this research was to obtain a better understanding of the sand boil problem. This dissertation explored the following two questions: (1) Is transient flow analysis due to river head fluctuations critical in the development of exit hydraulic gradients and the subsequent sand boil formation? and (2) If sand boils develop more frequently due to cumulative effects associated with repetitive flood events, how can transient flow analysis in conjunction with current underseepage analysis tools respond to this problem? Both questions were addressed by developing transient flow models and comparing them with current underseepage analysis tools. The transient flow models developed in this study are also expected to contribute to the current literature on analytical techniques for seepage problems. The following specific objectives were established for this study:

1. develop an analytical model to describe hydraulic head in response to river head fluctuations in a confined aquifer under a levee,
2. develop an analytical model to describe hydraulic head in response to river head fluctuations under a levee with leakage out of a confined aquifer,
3. construct time-dependent flow nets for underseepage analysis,
4. evaluate the performance of these analytical models by comparing them with other current practice underseepage analysis methods, and
5. evaluate possible cumulative effects in hydraulic head development with new analytical models and other underseepage analysis methods.

## **1.2 Outline of Dissertation**

The dissertation is organized as follows: This chapter gives an introduction to the research, an outline of the problem, the main questions asked, and the specific objectives of the study.

The second chapter gives background information and literature review. It provides detailed information on seepage erosion, previous studies on underseepage of levees conducted by USACE, current underseepage analysis tools, analytical studies on transient flow, and possible cumulative effects due to repetitive flood events.

The third and fourth chapters present transient analytical hydraulic head models; for a confined aquifer in the third chapter and with leakage out of a confined aquifer in the fourth chapter. In both, a solution with Laplace transform method and an approximate solution are presented. The fifth chapter details analytical construction of transient flow nets for infinite-depth aquifers and finite-depth aquifers. The results and a discussion about the transient models and flow nets are given in each chapter.

The sixth chapter provides a performance analysis of the developed models conducted by comparing the results of the analytical models with the USACE levee underseepage method and a finite element program. Results and discussion of this section explore the main question of this study: whether transient effects are critical in development of exit hydraulic gradients, which may trigger sand boil formation.

Cumulative effects due to repetitive flood events are discussed in the seventh chapter and are evaluated by transient flow models, USACE levee underseepage method, and a finite element program. The results and discussion of these evaluations explore the second question of this study: how transient flow analysis and current underseepage

analysis tools respond to possible cumulative effects due to repetitive flood events. The conclusions are presented in the eighth chapter.

There are four appendices containing details of mathematical computations and finite element models.

### **1.3 Scope of Study**

This research involved the use of mathematical models, which were supplemented by data from published on-site investigations.

Typical geological features of Mississippi River Valley include a less permeable top stratum and a more pervious substratum. This geological feature may allows us to do confined flow analysis. In the analytical models, linear laws of seepage were studied, where there is a linear relationship between seepage velocity and hydraulic gradient. The pervious substratum typically combines horizontally stratified beds of sand where horizontal conductivity of the main aquifer is so large compared to hydraulic conductivity of the semi-pervious top stratum. Therefore, it is safe to assume that horizontal flow in the pervious substratum is refracted over  $90^0$  to seep vertically through the semi-confining layer due to hydraulic uplift forces (Hantush and Jacob, 1955). While, all groundwater flow in nature is three-dimensional to a certain extent, symmetry features, i.e. flow to a well, make the problem possible to analyze in two-dimensional form (De Wiest, 1965). The solution may need to be further simplified by reducing the dimensionality of the problem to one due to difficult boundary conditions. Reducing the dimensionality of the problem introduce significant errors and it is up to hydrologists' judgement to estimate the error in engineering practice. In the light of this discussion, certain simplifications were applied in the development of analytical models in this research.

The analytical models for transient flow in a confined aquifer were developed by using the diffusion equation, which was derived under Darcy's law, and the law of conservation of mass. The geologic conditions beneath the levees can be very complex. To simplify the problem the stratum was assumed as saturated, homogenous, and isotropic, and the flow is assumed as one-dimensional. Transient analytical flow models with leakage out of a confined aquifer were presented and a subsurface system with a leaky confined aquifer and a semi-permeable layer on the top of it was considered. The assumptions introduced by Hantush and Jacob (1955) on leaky aquifer systems - that storage in the semi-permeable layer is negligible and the leakage is linearly proportional to the difference in head between two layers - are applicable here.

The methodologies given by Polubarinova-Kochina (1962) were followed for transient analytical flow nets for infinite and finite depth aquifers. The assumptions and the conditions in her solutions were maintained. A downward vertical flow at the riverside of the levee, a horizontal flow under the levee and an upward vertical flow at the landside of levee were assumed. The solution is for homogenous and isotropic soil conditions.

The performance of the analytical models was compared with the other seepage analysis tools. Even though a simple cross-section with typical soil parameters was used, the comparisons may not reflect identical conditions as each method was developed under its own assumptions. The transient flow models and other seepage analysis tools were used to evaluate possible cumulative effects of flood-induced seepage. As explained in the literature survey, there is a distinct lack of published studies on cumulative effects of underseepage problems associated with sand boils. The best evaluation of cumulative effects can be conducted by examining data from long-term site investigations and by

conducting laboratory experiments. The evaluation of cumulative effects by empirical, analytical and numerical methods is complicated. The transient analytical models developed in this study attempt to provide a view to the problem of evaluating cumulative effects of sand boils. Further research is needed in this area.



## CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

### 2.1 Introduction

The following items are reviewed in this chapter: seepage erosion mechanisms; levee underseepage and sand boil formation; field observations; soil properties susceptible to piping problem; geology of Lower Mississippi River Valley and its influence on underseepage; previous studies on levee underseepage conducted by USACE; current underseepage analysis methods; analytical studies on transient flow with cyclical boundary conditions; and cumulative effects. A list of symbols is included at the end of the chapter.

### 2.2 Seepage Erosion

Van Zyl and Harr (1981) classified seepage erosion failures into three modes: heave, piping and internal erosion. Heave is analyzed by comparison of seepage force per unit volume with effective unit weight of selected critical volume of soil. Terzaghi (1929) presented an exit gradient approach to seepage analysis in his classical work on failure of dams by seepage erosion. His theoretical development was based on the summation of the vertical seepage forces exerted by the upward flow of water and the vertical downward weight of the submerged soil. He defined the critical gradient to cause heaving as:

$$i_c = \frac{\gamma_{sub}}{\gamma_w} = \frac{G_s - 1}{1 + e} \quad (2.1)$$

where,  $\gamma_{sub}$  is the submerged unit weight of soil,  $\gamma_w$  is the unit weight of water,  $G_s$  is the specific gravity of soil, and  $e$  is the void ratio of soil. For typical soils, the critical gradient is approximately 1.0.

Sherard *et al.* (1963) investigated the mechanics of piping in earth and earth-rock dams. As water flows, the pressure head is dissipated in overcoming viscous drag forces, which resist the flow through the small pores. The seeping water also generates erosive forces and tends to drag the soil particles with it as it travels through the pervious layer. If the seepage erosive forces are greater than the erosion resisting forces, the soil particles are washed away and piping starts. If the soil has some cohesion, a small tunnel or pipe can form at the downstream exit face of a seepage path. Once piping starts, the flow in the pipe increases due to the decreased resistance to flow, piping accelerates, and the small tunnel or pipe lengthens. Van Zyl and Harr (1981) stated that the analysis of piping erosion was almost impossible due to control by discontinuities. However, global gradient approaches developed by Bligh (1927) and Lane (1935) are still widely used in the design of dams and weirs. The concept of the length of the path traveled by seeping water led to the development of creep ratios or creep coefficients. Bligh (1927) defined a creep coefficient as:

$$C = \frac{L}{h} \quad (2.2)$$

where  $L$  is the length of seepage path measured along the base of weir, and  $h$  is the total head loss. Lane (1935) suggested a weighted creep ratio as:

$$C_w = \frac{\frac{L_h}{3} + L_v}{h} \quad (2.3)$$

where,  $L_h$  is distance along horizontal contacts ( $<45^\circ$ , measured from the horizontal),  $L_v$  is distance along vertical contacts ( $>45^\circ$ ) and  $h$  is total head loss. Bligh (1927) and Lane (1935) suggested limiting values for creep coefficients obtained by analyzing a large number of structures founded on various soil conditions. Some typical values of weighted

creep ratio are: 8.5 to 5.0 for very fine sand to coarse sand, 4.0 to 2.5 for fine gravel to boulders, and 1.8 for hard clay (Lane, 1935).

Internal erosion begins locally by fine particles being moved from the soil matrix into a coarser layer leading to formation of cavities, collapse and failure. The mechanism is an important concern for the analysis of seepage through the hydraulic structures in the event of transfer of particles between zones of earth and rock-fill dams, and in dispersive soils (Sherard *et al.*, 1972). While the analysis of internal erosion is generally very difficult, installation of filters designed to proper filter criteria is the common prevention technique (Van Zyl and Harr, 1981).

Casagrande (1937) estimated the exit gradient from flow nets. Khosla *et al.* (1936) and Harr (1962) suggested theoretical methods to determine the exit gradients for confined flow for specific cross-sections. Khilar *et al.* (1985) investigated the potential for clay soils to pipe or plug under induced flow gradients. They presented the following equation as a measure of the critical gradient to cause piping:

$$i_c = \frac{\tau_c}{2.878\gamma_w} \left( \frac{n_0}{k_0} \right)^{1/2} \quad (2.4)$$

where  $\tau_c$  is the critical tractive shear stress (dynes/cm<sup>2</sup>),  $n_0$  is the initial porosity, and  $k_0$  is the initial intrinsic permeability (a typical value is,  $k_0 = 10^{-10}$  cm<sup>2</sup>). For granular materials, critical tractive shear stress can be estimated from the  $d_{50}$  size (Lane, 1935) as  $\tau_c$  (dynes/cm<sup>2</sup>) =  $10d_{50}$  (mm). Aralunandan and Perry (1983) studied the erodibility of core materials in earth and rock dams. They reported that the erosion resistant soils have a critical tractive shear stress of  $\tau_c \geq 9$  dynes/cm<sup>2</sup> based on limited data.

Soil type, rate of head increase and the flow condition are the main dependents for modes of seepage erosion failure (Van Zyl and Harr, 1981). The soil type controls

whether heave is followed by a quick condition as in clean sand or whether heave leads to crack formation, concentrated flow and piping. Heave, leading to cracks, concentrated flow and piping, appears to be more common in granular soils with a large percentage of fines.

A rapid increase in head may result in heave of the surface, leading to a quick condition (Van Zyl and Harr, 1981). This could be a typical failure condition on the downstream side of a water retention structure being filled rapidly. A quick condition before heave can also be produced when the head is raised very slowly. Tomlinson and Vaid (2000) presented an experimental study of piping erosion. They tested various artificial granular filter and base soil combinations in a permeameter under variable confining pressures to determine the critical gradient where soil erodes through the filter. They observed that the critical gradient was lower if the head was rapidly increased. Van Zyl and Harr (1981) also pointed out the importance of flow conditions in piping problems. According to the field observations, an unsaturated soil fails at lower gradients than the critical gradient of the soil. The first filling of a reservoir may induce this type of failure.

Sellmeijer and Koenders (1991) stated that empirically, a so-called piping channel or slit develops, extending from the downstream corner of the structure to a length of less than half the bottom length of a dam. They presented a mathematical model for piping. They modeled a prediction of an equilibrium situation in which some materials have washed away from underneath the structure and the channel development has stopped. The result of this study was a mathematical representation of the relation between the pipe length and the difference in water head. Ojha *et al.* (2001) developed a piping model based on Darcy's law. They concluded that the choice of permeability function was

critical for the piping model. The permeability functions, which depend only on grain size, have limited value on clarifying piping models while those that include porosity are more useful.

### **2.3 Development of Underseepage and Sand Boils**

Turnbull and Mansur (1961) explained underseepage mechanisms and sand boil formation at Mississippi River levees as a result of the studies and investigations conducted by the Army Corps of Engineers covering a period of 1937 to 1952:

“Whenever a levee is subjected to a differential hydrostatic head of water as a result of river stages higher than the surrounding land, seepage enters the pervious substratum through the bed of the river and riverside borrow pits or the riverside top stratum or both, and creates an artesian head and hydraulic gradient in the sand stratum under the levee. This gradient causes a flow of seepage beneath the levee and the development of excess pressures landward thereof. If the hydrostatic pressure in the pervious substratum landward of the levee becomes greater than the submerged weight of the top stratum, the excess pressure will cause heaving of the top blanket, or will cause it to rupture at one or more weak spots with a resulting concentration of seepage flow in the form of sand boils.

“In nature, seepage usually concentrates along the landside toe of the levee, at thin or weak spots in the top stratum, and adjacent to clay-filled swales or channels. Where seepage is concentrated to the extent that turbulent flow is created, the flow will cause erosion in the top stratum and development of a channel down into the underlying silts and fine sands, which frequently exist immediately beneath the top stratum. As the channel increases in size or length, or both, a progressively greater concentration of seepage flows into it with a consequent greater tendency for erosion to progress beneath the levee.

“The amount of seepage and uplift hydrostatic pressure that may develop landward of a levee is related to the river stage, location of seepage entrance, thickness and perviousness of the substratum and of the landside top stratum, underground storage, and geological features. Other factors contributing to the activity of the sand boils caused by seepage and hydrostatic pressure are the degree of seepage concentration and the velocity of flow emerging from the boils.”

Turnbull and Mansur (1961) also explained the importance of underground storage on underseepage and excess hydrostatic pressure during relatively low high waters and high waters of short duration. They noted that during a high water, if the ground water table is low, drainage into subsurface storage landward of the levee reduces

hydrostatic pressures and seepage rising to the surface. However, if the ground water table is high or the flood is of long duration, this factor has little effect on substratum hydrostatic pressures. In general, piezometric data obtained during the 1950 high water indicated that ground water storage landward of the levees was filled by the time a high flood stage developed.

The critical gradient required to cause sand boils or heaving is estimated by Equation 2.1. Approximate theoretical critical gradients for silty sands and silts is approximately 0.85 and for silty clay and clay is 0.80 (Turnbull and Mansur, 1961). In the field, the critical gradient required to cause sand boils can best be determined by measuring the hydrostatic head beneath the top stratum at the time a sand boil starts. The critical gradient in the field is determined by

$$i_c = \frac{h_x}{z_t} \quad (2.5)$$

where  $h_x$  is the head beneath top stratum at distance  $x$  landward from landside toe of the levee, and  $z_t$  is the thickness of landside top stratum.

### **2.3.1 Field Observations of Underseepage and Sand Boils**

Mansur, *et al.* (2000) reviewed studies carried out since the 1940's on underseepage, piping, and sand boil formation in the Mississippi River Valley. The Mississippi River floods of 1993 produced seepage under some levees which resulted in dramatic levee failures in the Kaskasia Island Levee District in Illinois (Mansur, *et al.*, 2000). A sand boil and subsurface piping caused the Kaskasia Island levee to fail, flooding the entire levee district.

According to witnesses, levee failures due to high water usually starts with sand boil occurrences near the toe of the levee, followed by overtopping. In some cases, the

river does not rise above the top of the levee; rather, the levee fails, sinking below the prior river levee elevation. Much sand boil information is derived from observational data based on subjective descriptions by different people and usually does not represent observations made on a continual basis. Mansur *et al.* (2000) gathered sand boil information for seven levee districts after the 1993 high water. Uplift gradients calculated from existing piezometers showed that significant sand boils were observed when uplift gradients were in the range of 0.58 to 0.84.

Mr. Richard Meehan, instructor at Stanford University, California, with USACE background, worked on Feather River hydrographs at levee breaks. Levees near Marysville and Yuba City, California, failed in 1955, 1986, and 1997. The investigators compared the flood hydrographs. The 1955 and 1997 levee failures occurred at just about the time the river stage made its peak. In 1986, floodwaters began to recede, then failure occurred one day after the river stage made its peak. This investigation suggests that the pressures causing failure may lag behind the immediate flood pressures on the levee. For all the failures, the levees were not overtopped but sand boils had been observed at the toe of the levee before failure.

The Mississippi River floods of 1997 resulted in seepage under certain levees in Louisiana, especially those near Angola Prison. The levee at this location developed sand boils, leading to emergency repairs to prevent levee failure.

Li *et al.* (1996) studied widely reported sand boils north of Cairo, Illinois, where 4 m of head existed between the river and the landward ground surface in 1993. The researchers examined sand boils along the Mississippi River levee west of Ware, Illinois. Sand boils were abundant within 5 m of the levee toe, only small pin boils were observed at a distance of 100 m from the levee, and beyond 100 m, there was no significant

evidence of surface seepage. Li *et al.* reported the sand boils had dimensions with 0.5 m to 10 m diameter, and they commonly extended 0.3 m above the ground surface. Mansur *et al.* (2000) reported the results of an underseepage and sand boil study after the 1993 high water. The dimensions of many sand boils were up to 30" in diameter at Prairie DuPont and Ft. Chartres Levee Districts, Illinois. At the other regions of Mississippi River levees, many sand boils of 2" to 12" in diameter were observed. Another observation of sand boils was reported by the Corps of Engineers after 1997 high water. A sand boil with a throat of 0.45 m to 0.6 m (1.5 to 2.0 ft) in diameter was observed at about 60 m (200 ft) from the levee at Blue Lake, Arkansas. The uncontrolled flow resembled a large relief well and approximately 23 cu.m (30 cu.yd) of fine to medium sand was deposited.

The U.S. Army Corps of Engineers, New Orleans District Office, conducted a seepage study from Louisiana State University (LSU) to Duncan Point of Pontchartrain Levee District in 1992. This study references data back to a technical manual, TM 3-424 published by USACE in 1956. During the 1937 high water, improperly backfilled seismic shot holes near the LSU campus were attributed as being the cause for sand boils experienced. During the 1950 high water, excess hydrostatic pressures of 12.5 to 15 ft existed along the landside toe of the levee. This hydrostatic pressure corresponds to 75% to 90% of the crest head in the river. Excess heads of 10 to 12 ft were also observed as far as 0.75 mile (1.2 km) landward of the levee. During the 1950 high water, four fairly large sand boils were observed but according to the available records they were not at the same locations as the 1937 boils. During the 1973 high water, sand boils were observed at fairly large distances up to 2.4 km from the levee. In 1975, a sand boil nicknamed "Big Mamou" developed at about 1 mile (1.6 km) from the levee along the banks of Elbow



Bayou due to high water. During the 1983 high water, there was no flow from Big Mamou but a new sand boil developed about 200-ft (61 m) away from it. Again in 1983, a sand boil about 0.5 mile from the levee, which developed at LSU stadium parking lot, was flowing clear.

In 1992, the USACE noted that the studied regions of levees have a relatively thick soil blanket, which is sufficient to withstand high hydrostatic pressures. This fact explains the occurrence of high hydrostatic pressures and sand boils as far as a mile from the levee, where the soil blanket may be thinner. This study concluded that seepage prevention methods, such as seepage berms and relief wells, protect limited areas. Seepage berms may force seepage away from the levees, and relief wells along the landside toe of a levee only create a “dip” in the hydrostatic gradient line.

Recent observations were also conducted at LSU Dairy Farm in July 2002 by Dr. Dean Adrian, Professor, and Senda Ozkan and Curtis Sutherland, graduate students at LSU. A sand boil near a drainage channel was observed about 0.5 mile away from the Mississippi River levee. Apparently, soil under the sand boil was eroded, then discharged into the drainage channel next to the boil. The sand boil turned into a sinkhole (Figure 2.1). The dimensions of the sinkhole were about 4 ft deep, 6 ft wide and 10 ft long. According to the observations, as the water level in the river rose, there was bubbling water at the bottom of the hole, then the accumulated water in the hole drained to the drainage ditch. Later, the sand boil depression was repaired and a relief well was installed (Figure 2.2). It is interesting to note that there is a wastewater lagoon close to the sand boil. However, the water in the sand boil looked fresh and clean, suggesting no flow was leaking from the lagoon into the boil, but instead, water was seeping from the river.



**Fig. 2.1 A sand boil turned into a sinkhole at LSU Dairy Farm (July 2002). The sinkhole had been filled before, but reformed after several years.**



**Fig. 2.2 A relief well was installed into the sinkhole at LSU Dairy Farm (August 2002).**

### 2.3.2 Soil Properties Susceptible to Piping

Peter (1974) examined the conditions associated with piping phenomena in the subsoil, near levees in the Mississippi River region, and in the Danube River region in former Czechoslovakia, Hungary and Yugoslavia. The studies showed that the grain size distribution curves are one of the most appropriate aids for judging the danger of piping problems. From the coefficient of uniformity of the soil,  $C_u$  and the coefficient of curvature,  $C_c$ , the danger can be determined. The coefficient of uniformity and the coefficient of curvature are defined as:

$$C_u = \frac{d_{60}}{d_{10}} \quad (2.6)$$

$$C_c = \frac{d_{30}^2}{d_{10}d_{60}} \quad (2.7)$$

A geological condition favorable for the formation of piping is very permeable sandy gravel which has a substantial amount of fine particles,  $d_{10} = 0.25$  mm, the coefficient of uniformity,  $C_u > 20$ , the coefficient of curvature,  $C_c > 3$ , and there is a lack of grains of size 0.5 to 2 mm. The pipings in the Danube River levees are connected with geologic conditions similar to those of pipings near the Mississippi River (Peter, 1974).

De Wit *et al.* (1981) conducted laboratory research on piping on a scale model with fine, medium and coarse sand. In general, they observed higher critical exit gradients for the coarser and the denser sand. They also found that when two sands are compared having the same grain size distribution curve, the sand with the higher angle of friction exhibits a higher critical gradient.

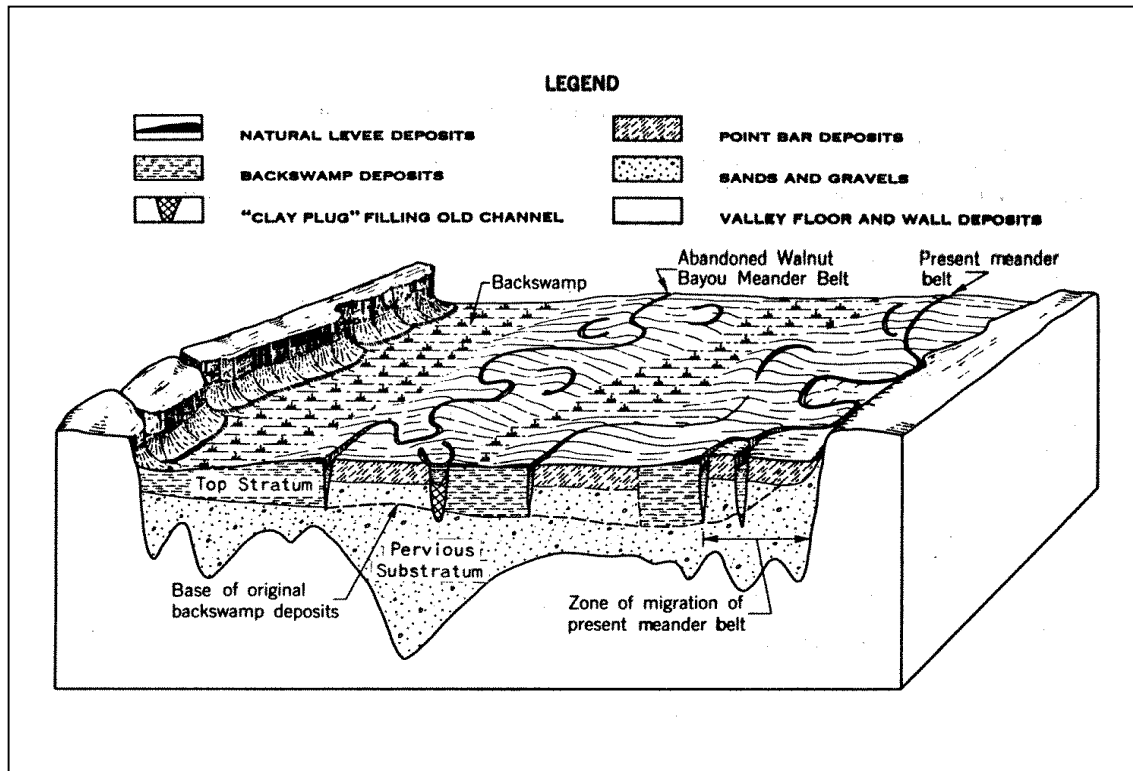
A grain-size analysis on one sand boil observed during Mississippi River Flood of 1993 showed that 98% by weight of eroded grains were smaller than 0.125 mm in diameter (Li *et al.*, 1993).

Sherard *et al.* (1972) studied piping in earth dams of dispersive clays. Some natural clay soils disperse in the presence of water and become highly susceptible to erosion and piping. The tendency of dispersive erosion in a given soil depends upon variables, such as mineralogy, chemistry of clay, and the amount of dissolved salts in the soil pore water and eroding water. The susceptibility of a fine grained soil to internal erosion increases with the tendency of its particles to disperse either spontaneously with the presence of water or under the drag force of seepage. Non-cohesive silt, rock flour, and very fine sands also disperse in water and may be highly erosive.

#### **2.4 Geology of the Lower Mississippi River Valley and Its Influence on Underseepage**

The U.S. Army Corps of Engineer conducted investigations of the geologic conditions of Lower Mississippi River Valley in 1940's. Geological studies at several sites along the Mississippi River levees showed that there were significant correlations between the distribution of alluvial deposits of sand, silt and clay, and the occurrence of underseepage and sand boils (Turnbull and Mansur, 1961; Kolb, 1973). The Alluvial Valley of Lower Mississippi is about 500 miles long and 50 miles wide on average. The valley begins at the confluence of the Mississippi and Ohio rivers at Cairo, Illinois, and extends to the Gulf of Mexico. The alluvial deposits in the Lower Mississippi River Valley fill a trench ranging in the depth from 100 ft to 400 ft. The alluvial fill was formed about 30,000 years ago, when the glaciers of late Wisconsin stage began to melt, the sea level gradually rose causing the entrenched valley to become filled with sandy gravels,

sands, silts and clays that can be grouped as a sand and gravel substratum and a fine-grained top stratum. Turnbull and Mansur (1961) presented an illustration of the entrenched valley and alluvial fill as in Fig. 2.3.



**Fig. 2.3 Block diagram of Alluvial Valley of the Lower Mississippi River. The section is at about latitude of Natchez, MS (Turnbull and Mansur, 1961).**

The gravel and coarse sand to fine sand substratum has a high seepage carrying capacity. The top of the pervious substratum is considered to be the uppermost portion of the aquifer having a  $d_{10} > 0.15$  mm or a hydraulic conductivity of  $k > 0.05$  cm/sec. The bottom of the substratum or alluvial valley is taken as the contact between the sand and gravel substratum and the underlying rock. The thickness of sandy alluvium ranges from 75 ft to 150 ft. In design computations, the average hydraulic conductivity of the sandy alluvium was taken as 0.1 cm/sec based on laboratory tests in the 1950's. After relief wells were installed this value was found to be around 0.15 cm/sec (Turnbull and

Mansur, 1961). The top stratum usually consists of several layers of clay, sandy silt and silty sand layers. About 6000 years ago, the sea level reached its present position, rapid filling of the entrenched valley ceased, and the former braided channel was replaced by a meandering stream that deposited sediments including point bar, channel fill, natural levee, and backswamp deposits. The point bar deposits are fine grained deposits with a thickness of 10 ft to 20 ft; the channel fill deposits are relatively impermeable silts and clays with a 55 ft to 125 ft depth; the natural levees are sandy silt and silty clays with a 5 ft to 10 ft depth in the Lower Mississippi Valley. The backswamp deposits are silts and clays with 15 ft to 70 ft depth in southern Louisiana.

Sand boil formation at the landside of a levee is influenced by a number of factors, including: (i) configurations of geological features such as swales and channel fillings and their alignment relative to the levee; (ii) characteristics and thickness of the top stratum; (iii) man made works such as borrow pits, post holes, seismic shot holes, and ditches; (iv) cracks and fissures formed by drying and other natural causes; and (v) organic agencies, such as decay of roots, uprooting of trees, animal burrows, and holes dug by crawfish. In general, the seepage is greatly concentrated along the edges of swales and the landside levee toe (Turnbull and Mansur, 1961; Cunny, 1980).

Kolb (1976) studied underseepage data collected by the USACE Vicksburg District during the 1973 flood along a randomly selected 40-mile stretch of river. He noted that point bar deposits are thin enough and permeable enough to cause underseepage problems. During the 1973 flood, significant underseepage was confined almost entirely to areas where point bar deposits underlie the levee. He presented several alignments of geological features beneath the levees and showed the concentrated sand boils reported at those areas. Figure 2.4 shows how clay channel fillings and swales can

cross beneath levees at an acute angle; sand boils tend to form in point bar deposits within the angle between these layers. A borrow pit at the riverside of the levee is important in initiating and increasing underseepage in Fig. 2.4. Expanded section A-A' shows a semi-pervious natural levee deposit lying between the backswamp clays and the artificial levee where seepage may occur in the extreme landward portions of the natural levee and in old natural levee crevasses backfilled with sand (Kolb, 1976). Borrow pits on the riverside of the levee that have had their impervious top stratum removed may accelerate the problem in this figure. Where swales and channel fill clays cross beneath the levees at approximately right angles (Fig. 2.5), the sand boils are randomly dispersed and not as frequent and severe as when there is an acute angle between the levee and clay bodies. Note also that an oxbow lake partially filling an abandoned channel is an important source for seepage in Fig. 2.5. Kolb (1976) also pointed out a case where drainage ditches penetrating fairly permeable materials on the landside of the levees may cause heavy seepage and sand boil formation (Fig. 2.6).

In the conclusion of his work, Kolb (1976) stated that the disposition of pervious versus impervious floodplain deposits beneath the levee and the angle at which such deposits are crossed by the overlying levees controls the position of sand boils. He also suggested that corrective design of levees should include: (1) a detailed delineation of the surface and subsurface geology; (2) a careful selection of borrow pits to avoid stripping critically thin top-stratum deposits; and (3) the use of riverside or landside berms or blankets, and/or installation of relief wells.

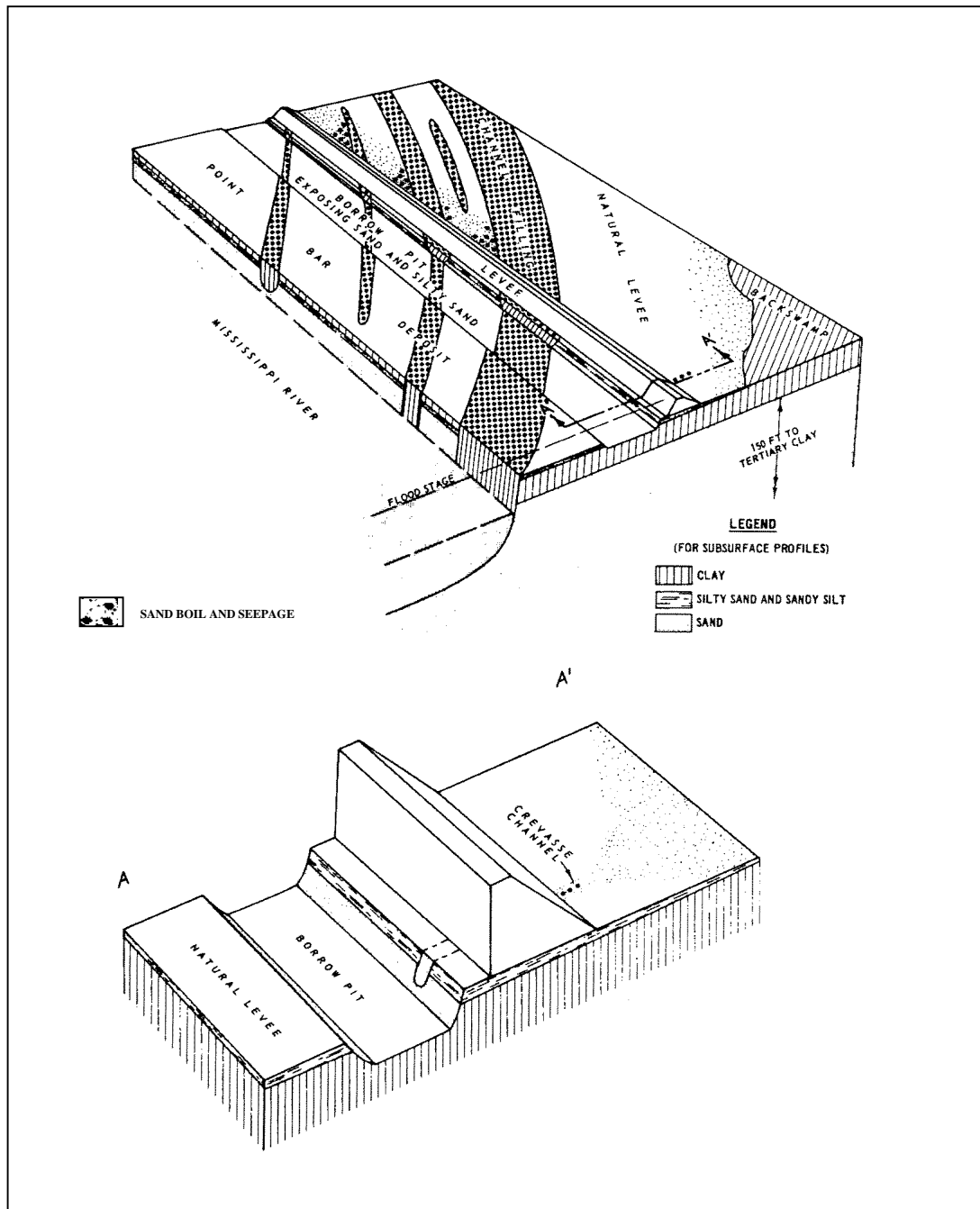
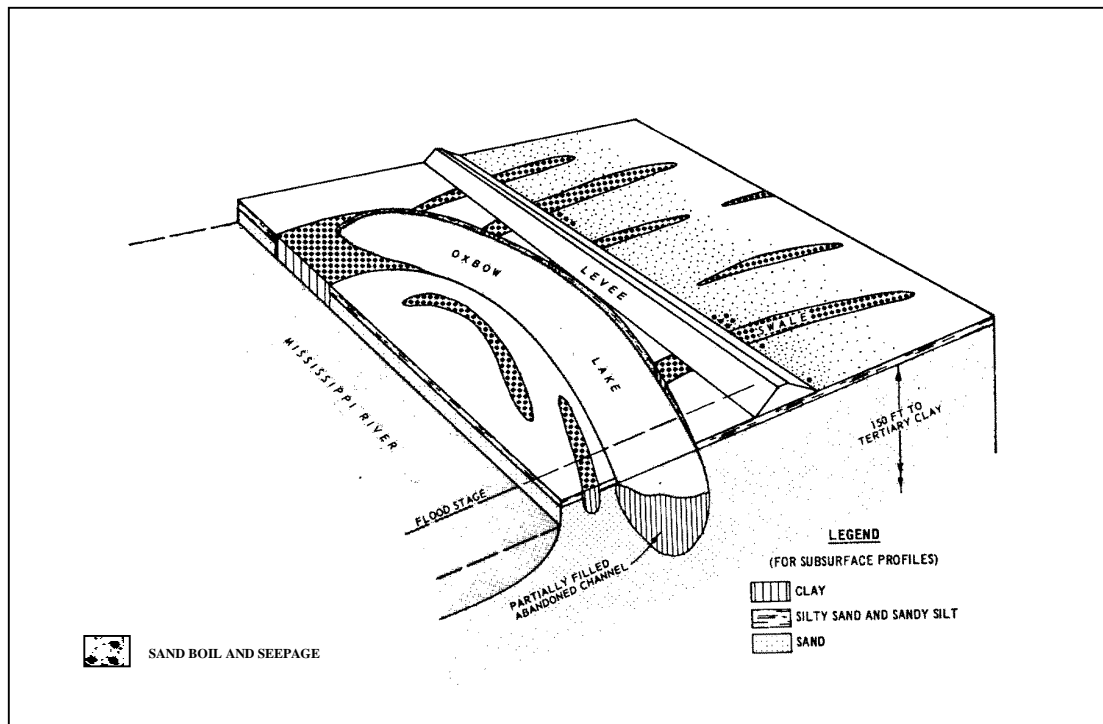
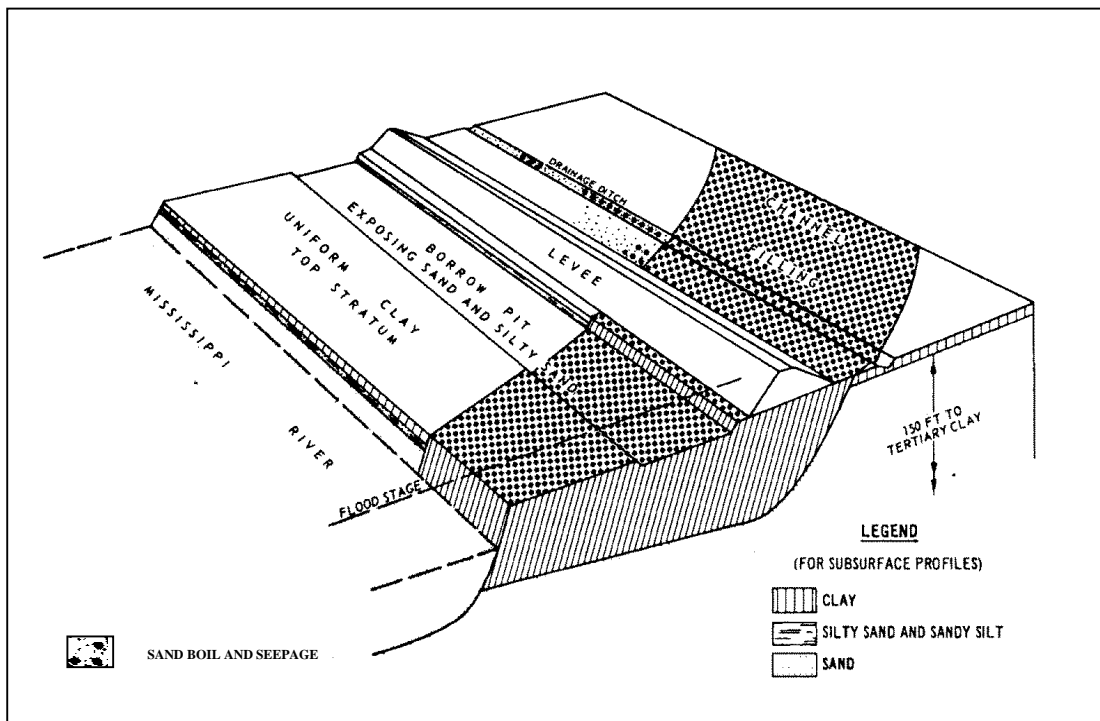


Fig. 2.4 Clay channel fillings and swales crossing beneath levees at an angle (Kolb, 1976).





**Fig. 2.5 Swales and channel fill clays cross beneath the levees at more or less right angles (Kolb, 1976).**



**Fig. 2.6 Drainage ditch penetrating fairly permeable materials on the landside of the levee (Kolb, 1976).**

## **2.5 Previous Studies on Levee Underseepage Conducted by USACE**

The first investigation of potential levee underseepage was initiated by the USACE Mississippi River Commission in 1937 in response to problems caused by high water conditions. More detailed study was carried out by the USACE Waterways Experiment Station (WES), Vicksburg, MS in the 1940's. Procedures to evaluate the quantity of underseepage, uplift pressures and hydraulic gradients were developed based on closed-form solutions for differential equations of seepage flow presented by Bennett (1946). In 1956, a technical memorandum, TM 3-424 was published by the USACE Waterways Experiment Station documenting the analysis of underseepage and design of control measures for Lower Mississippi Valley levees (Mansur *et al.* 1956). In this document, the top stratum landside of levees is classified into one of three categories: (1) no top stratum; (2) top stratum of insufficient thickness to resist hydrostatic pressures that can develop; and (3) top stratum of sufficient thickness to resist hydrostatic pressures that can develop during the maximum design flood. Kolb (1976) discussed underseepage data collected by USACE Vicksburg District along a randomly selected 40-mile reach of the river during the 1973 flood. He pointed out the most dangerous top stratum category as the second category listed by Mansur *et al.*, 1956. In this category, artesian pressures can build up beneath the top stratum landside of the levee to a range of 25% to 75% of the net head on the levee, and may extend significant distances landward of a levee.

Mansur *et al.* (1956) classified seepage as heavy, medium and light. Turnbull and Mansur (1961) presented seepage conditions and upward gradients through the top stratum measured by piezometers during the 1950 high water (Table 2.1). During the high water of 1950, sand boils were observed in a hydraulic gradient range of 0.5 to 0.8. In developing these seepage conditions, sites were eliminated where the top stratum

thickness was less than 5 ft or greater than 15 ft (Technical Letter, ETL 1110-2-555, 1997).

**Table 2.1 Seepage Conditions and Exit Gradients During the 1950 High Water (Turnbull and Mansur, 1961).**

Seepage Condition	Amount of Seepage (Q/H)	Exit Gradient
Light to no seepage	< 5 gal/min/100 ft of levee	0-0.5
Medium seepage	5 - 10 gal/min/100 ft of levee	0.2-0.6
Heavy seepage	> 10 gal/min/100 ft of levee	0.4-0.7

Turnbull and Mansur (1961) summarized the design and analysis procedure of levees presented in TM 3-424. Department of Army published in 1978 (and updated in 2000) an Engineer Manual (EM) 1110-2-1913 “Design and Construction of Levees”. Other than advanced numerical modeling, this Engineer Manual represents the state-of-practice analysis method for evaluating hydraulic gradient due to levee underseepage (Gabr *et al.*, 1996).

The Army Corps of Engineers investigated possible remedial measures to underseepage problems, which are discussed below. The most common underseepage control measures include pressure relief wells, landside seepage berms, riverside blankets, drainage blankets or trenches, cutoffs, and sublevees. Muskat (1937) presented a design methodology for relief wells. Middlebrooks and Jervis (1947) revised Muskat’s method to include partial penetration of the relief wells. Barron (1948) presented a design methodology for fully penetrating relief wells. The Department of the Army published Engineer Manual (EM) 1110-2-1905 “Design of Finite Relief Well Systems” in 1963 and EM 1110-2-1914 “Design, Construction, and Maintenance of Relief Wells” in 1992. Mansur *et al.* (1956) stated that pressure relief wells, riverside blankets, and

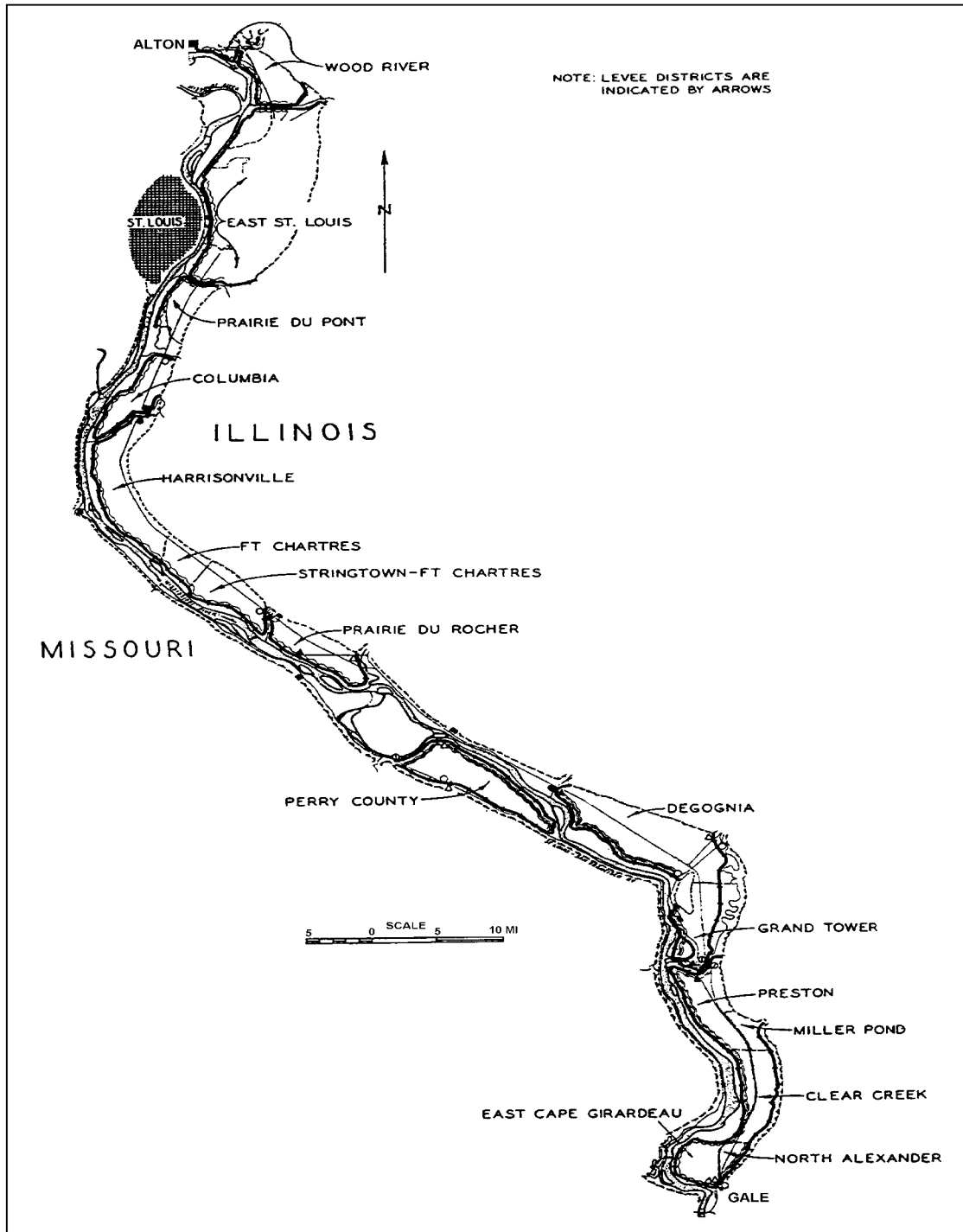
landside seepage berms are generally applicable for Mississippi River levees. Sublevees and drainage blankets or trenches are applicable in certain special situations.

Wolff (1974) and the U.S. Army Engineer District, St. Louis (1976) studied the performance of 200+ mile levee system along the middle Mississippi River from Alton to Gale (Fig. 2.7).

It was reported that the use of the Corps method outlined in Engineer Manual (EM) 1110-2-1913 resulted in a reliable design of levees. It was also concluded that the existing procedure has deficiencies in characterization of a two layer subsurface profile and the inability to model levee bends at corners. Cunny (1980) summarized piezometer data for levees in the Rock Island District, Illinois. Cunny reported that the probability of sand boil occurrence increases with geologic discontinuities. Daniel (1985) reviewed Cunny's report and the other Rock Island data and found that sand boils were observed at gradients ranging from 0.54 to 1.02. A similar statement was also reported earlier in TM 3-424.

Wolff (1987) studied the application of numerical methods to levee underseepage analysis and pointed out the advantages of special purpose computer programs over traditional underseepage analysis and general-purpose numerical analysis programs. Wolff (1989) developed the computer program LEVEEMSU for analysis of levee underseepage. LEVEEMSU was also used to analyze actual data at a number of levee reaches and back-calculate field permeability values. Cunny *et al.* (1989) also developed a computer program, LEVSEEP, to perform regular underseepage analysis outlined in EM 1110-2-1913, TM 3-424, EM 1110-2-1602, as well as to calculate reduced seepage quantities with the choice of control measures including seepage berms, riverside

blankets, cutoffs and relief wells. Later, Wolff and Taylor (1991) extended LEVEEMSU to analyze three-layer irregular foundation cases.



**Fig. 2.7 Plan of Levees Along Mississippi River, Alton to Gale, Illinois (after Mansur *et al.*, 2000).**

## 2.5 Current Underseepage Analysis Methods

In general, approximate methods of solution to confined flow problems include sketching flow nets, electrical analogs, method of fragments (Harr, 1962), viscous flow models such as Hele-Shaw models, relaxation methods (numerical analysis), and small-scale laboratory models. Advanced numerical modeling and 2-D finite element analysis programs provide sophisticated analysis of seepage flow. Boundary fitted coordinate methods also show promise as a method of analyzing seepage flow problems (Thompson *et al.* 1977; Thompson and Warsi, 1982; Thompson *et al.* 1985, and Hartono, 2002).

The transient effects in seepage have been studied under conditions of partial saturation (EM 1110-2-1901, Seepage Analysis and Control for Dams). The flow in partially or unsaturated soils is considered in a transient state. Therefore, transient effects in seepage are normally studied as the migration of a wetting front into unsaturated soils and variations in hydraulic conductivity according to soil water retention curves. Viscous flow models have been used to study transient flow (EM 1110-2-1901). A viscous flow model was constructed at USACE Waterways Experiment Station (WES) to simulate seepage conditions induced in streambanks by sudden drawdowns of the river level. The results from the model study were compared with field observations, finite difference, and finite element methods (Desai 1970, Desai 1973). Two and three-dimensional finite element seepage computer programs for confined and unconfined flow problems were developed at WES. Steady-state and transient problems can be solved with these computer programs (Tracy 1973a, Tracy 1973b). Transient problems can be treated as a series of steady-state problems. The studies lead by USACE formed a basis for further development of commonly used finite element seepage programs. GMS/SEEP2D is a 2D finite element model that can be used to model steady-state confined, partially confined

and unconfined flow. Another finite element seepage analysis program, SEEP/W performs transient seepage analysis considering hydraulic conductivity and water content changes as a function of pore water pressure. Complex geometries, non-homogenous, and anisotropic soil features can be modeled by these finite element models.

For seepage analysis under levees, U.S. Army Corps of Engineers, Design Guidance on Levees, EM 1110-2-1913, recommends use of numerical analysis models such as LEVSEEP and LEVEEMSU or finite element methods such as CSEEP which include two-layer or three-layer subsurface characterization (ETL 1110-2-555, 1997). The computer program LEVSEEP is based on the modeling of the steady-state flow domain with Bennett's (1946) analytical solutions for underseepage and the method of fragments for cutoff analyses. LEVSEEP provides similar analysis with the hand methods of analysis outlined in EM 1110-2-1913, EM 1110-2-1602, and TM 3-424 (Brizendine *et al.* 1995). LEVEEMSU is based on one-dimensional simplification of the steady-state flow domain using the finite difference method. LEVEEMSU solves Bennett's (1946) differential equation for irregular foundation geometry and non-uniform soil properties.

## **2.6 Analytical Studies on Transient Flow**

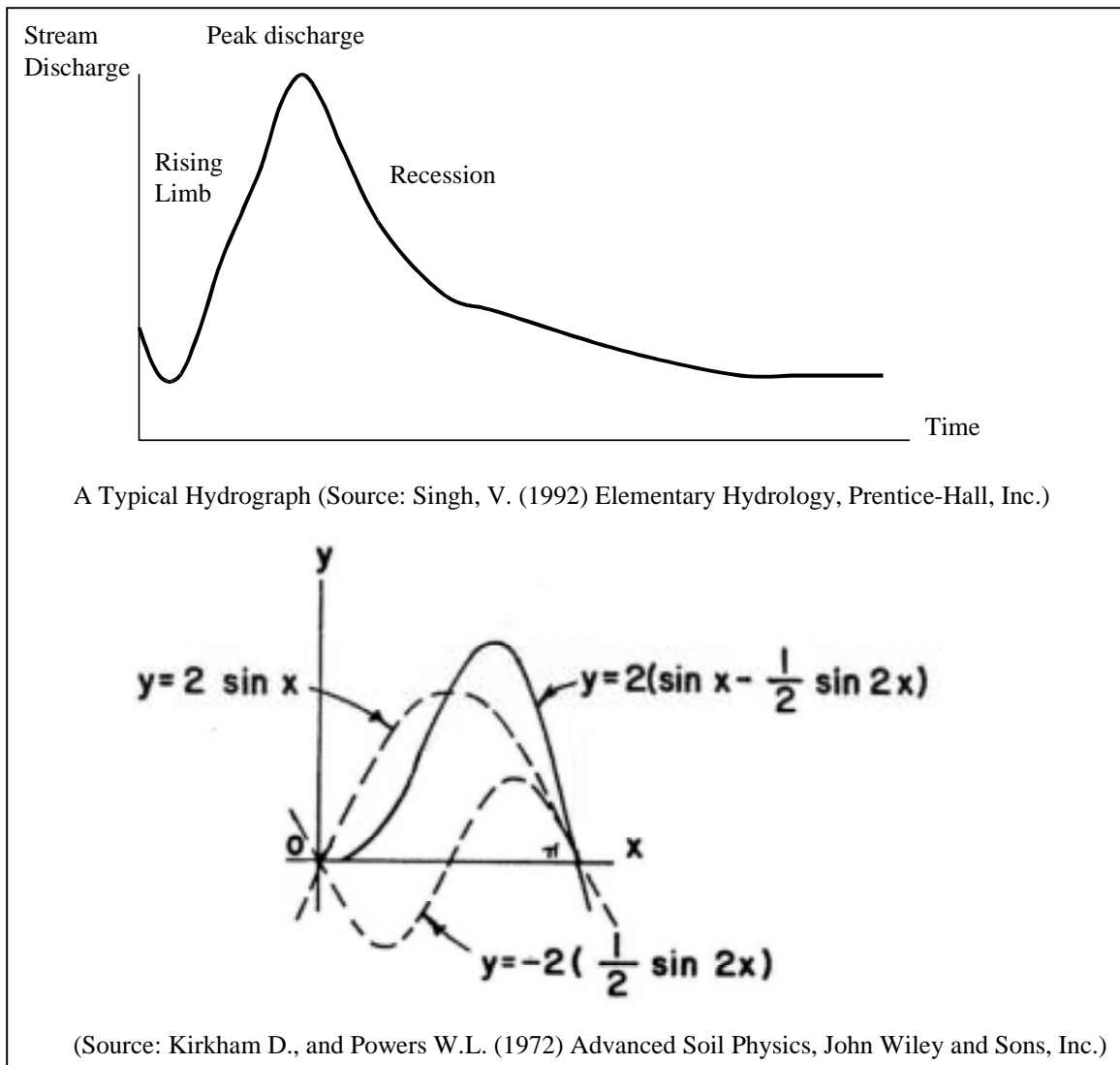
Cyclical boundary conditions represented by sinusoidal head functions represent one type of transient flow. The head profiles are described by the terms steady-state, quasi steady-state and unsteady state. The steady-state case represents the situation where there is no change in head profile with time. If the head profile is not steady-state, the alternative is the unsteady-state case. However, in engineering literature, quasi steady-state is a term used to describe the unsteady-state head profile that is generated with a cyclical boundary condition as time goes to infinity. Quasi steady-state is reached with a cyclical boundary condition when the head profile replicates itself within an acceptable

error tolerance with the frequency of cyclical head. Yu *et al.* (1991) used the term “memory time” and “memory length” to describe the time when the quasi steady-state condition exists at a certain location, and the distance from the boundary where the quasi steady-state profile is applicable at a certain time.

Water-level fluctuations in wells can be affected by such natural loading events as earthquakes, ocean and earth tides, changes in river stage, and atmospheric pressure (Domenico and Schwartz, 1998). These fluctuations are evidence that confined aquifers are not rigid bodies but that they respond to small changes in stress by being elastically compressible (Meinzer, 1928 ; Jacob, 1940). There are many examples of the response of water levels to natural events, such as the inland propagation of sinusoidal fluctuations of ground-water levels in response to tidal fluctuations of a simple harmonic motion (Ferris, 1951; Werner and Noren, 1951), and change in head in response to change in river stage (Cooper and Rorabaugh, 1963). These earlier studies of progressive waves in confined and unconfined aquifers caused by cyclical changes in river stage provide insight into solution of one-dimensional diffusion-type equations subject to sinusoidally varying boundary conditions.

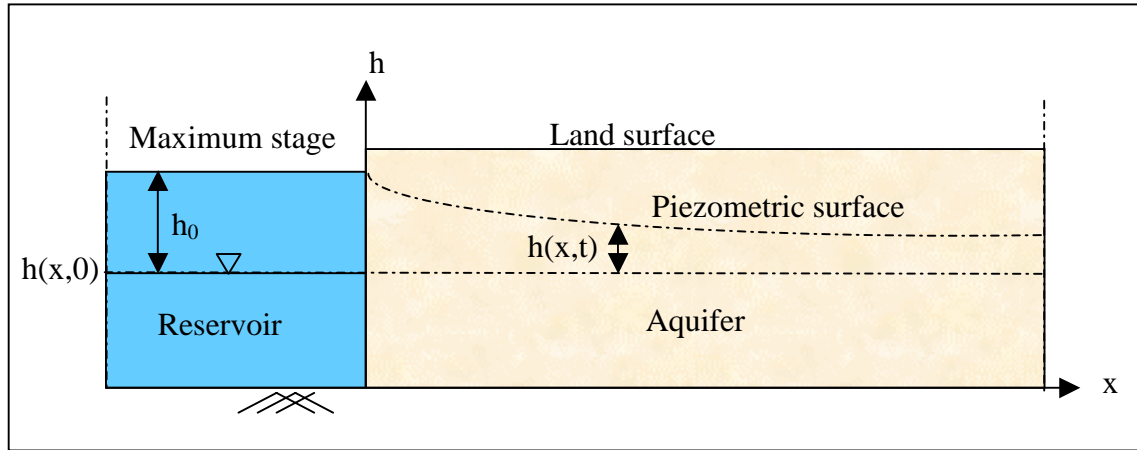
A typical hydrograph can be simulated by superposition of a series of sinusoidal fluctuations as shown in Fig. 2.8 (Singh, 1992). Superposition of more than two sinusoidal fluctuations can model more complex hydrograph shapes, and a Fourier series made up of an infinite series of sine and cosine functions can model any smooth function (Farlow, 1982).





**Fig. 2.8 Simulation of a typical hydrograph with a series of sinusoidal fluctuations.**

An idealized flow domain to analyze the transient effects of flood waves on groundwater flow is shown in Fig. 2.9. The aquifer is represented as a semi-infinite, horizontal confined aquifer of uniform thickness bounded on the left by an open boundary. In this case, the open boundary is a river. The water level in the river fluctuates and causes corresponding head fluctuations within the aquifer. From an analysis of aquifer response to the river fluctuations, transmissivity and storage coefficient of the aquifer can be estimated.



**Fig. 2.9 Representation of simplified one-dimensional flow as a function of surface-water stage (source: USACE, EM 1110-2-1421).**

One-dimensional flow is described in many textbooks by the equation for linear, non-steady flow in a confined aquifer:

$$\frac{\partial h}{\partial t} = \frac{T}{S} \frac{\partial^2 h}{\partial x^2} \quad (2.8)$$

where  $h$  is the rise or fall of hydraulic head in the aquifer,  $x$  is the distance from aquifer-river intersection,  $t$  is time,  $T$  is aquifer transmissivity, and  $S$  is aquifer storage coefficient. The solution of Equation 2.8 subject to a fluctuating boundary condition was presented by Ferris 1951; Cooper and Rorabough 1963; Pinder *et al.* 1969; and Hall and Moench 1972. Ferris (1951) observed that wells near bodies of tidal water often show sinusoidal fluctuations of water level in response to periodic changes in water stage. He presented a quasi steady-state solution to the problem. He also presented expressions to determine aquifer diffusivity ( $T/S$ ) based on the observed values of amplitude, lag, velocity, and wavelength of the sinusoidal changes in groundwater level. If the time lag between surface and groundwater maximum and minimum stages is known then aquifer diffusivity can be estimated by using the following formula (Engineer Manual, EM 1110-2-1421, Equation 6-9)

$$t_{lag} = d \sqrt{\frac{PS}{4\pi T}} \quad (2.9)$$

where  $t_{lag}$  is the lag time in occurrence of maximum groundwater stage following the occurrence of a similar surface stage,  $d$  is the distance from an observation well to the surface water, and  $P$  is the period of uniform tide or stage fluctuations.

Cooper and Rorabough (1963) presented a solution of Equation 2.8 for a single sinusoidal pulse of general form  $1 - \cos \omega t$ , where  $\omega$  is the frequency. Pinder *et al.* (1969) developed solutions to the governing equation using discrete steps approximation to fluctuations in the reservoir boundary. Hall and Moench (1972) applied a convolution equation to find head fluctuations in the aquifer due to an arbitrarily varying flood pulse. They derived equations for the instantaneous unit impulse response function, the unit step response function, and the derivative of unit step response function for finite and semi-finite aquifers, with or without semi-pervious stream banks.

More recently, Moench and Barlow (2000) presented Laplace transform step-response functions for various homogenous confined and leaky aquifer types and for anisotropic, homogenous unconfined aquifers interacting with perennial streams. They inverted the Laplace transform solutions numerically to obtain the real-time step-response functions for use in the convolution integral. Barlow *et al.* (2000) developed two computer programs on the basis of their real-time step-response functions presented in their companion paper of Moench and Barlow (2000). They used computer programs they developed to simulate the responses of hypothetical confined and water-table aquifers to sinusoidal-type flood waves.

As shapes of the stage hydrographs for flood waves vary, a solution of the governing equation with a boundary condition described by a uniform sine wave does not

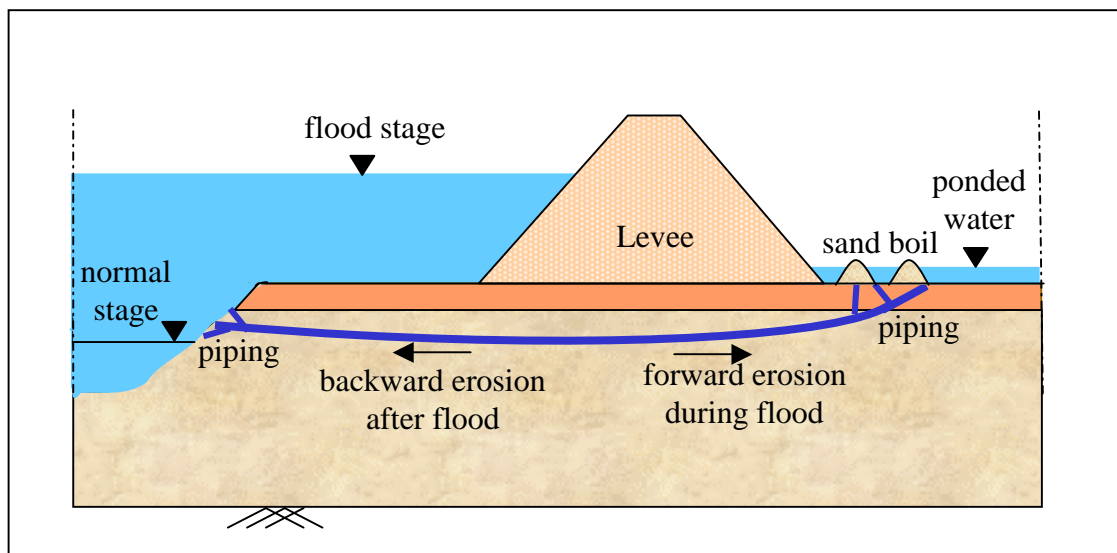
describe the actual domain adequately (Engineer Manual, EM 1110-2-1421). The discrete steps approach is not restricted to fluctuation of sinusoidal or uniform asymmetric curves and allows the use of a stage hydrograph of any shape. An alternative approach for representing the flood wave boundary has been shown in Figure 2.8.

Another application of cyclical boundary conditions in analytical solutions are the studies on tracer transport models in soils and contaminant transport in rivers. Logan *et al.* (1996) studied a one-dimensional model of transport of a chemical tracer in porous media with periodic Dirichlet and periodic flux type boundary conditions. Alshawabkeh and Adrian (1997) studied pollutant transport in a river subject to a sinusoidally varying boundary condition. They applied complex variables and the Laplace transform method to solve for the pollutant concentration distribution. Oppenheimer *et al.* (1999) proved that an unsteady-state solution approaches to the quasi steady-state solution with time. Adrian *et al.* (2001) developed a tracer transport model in a soil column with a periodic loading function, which varies as a sinusoidal curve. They solved the governing equation by applying superposition, Laplace transform and convolution integral, and introduced complex variables to evaluate the convolution integral.

## **2.8 Cumulative Effects**

Cumulative effects of seepage under levees can compromise levee safety. A stratum of sands under seepage flow begins to heave at a particular value of seepage. This heave is related to the size, velocity, and amount of particles that wash away (Peter, 1982). The deformation due to heave may be reversible; however, complete recovery of this expansion is unlikely. When the same stratum of sands is exposed to a subsequent flood, movement of fine particles is expected to be more severe than it was during a previous flood. Besides when piping is localized at the landside levee toe, even if there is

no external evidence of a sand boil, there are few if any mechanisms which would bring about healing of a pipe located immediately below a rigid, non-deforming levee. Peter (1982) also noted another serious problem that can contribute to cumulative effects. As the river level drops, the seepage water that had been on the landside may flow back from its former discharging point toward the river leading to backward erosion which may promote development of a pipe on the riverside of the levee. This erosion gradually enlarges and shortens the seepage channel and may cause additional cumulative changes leading to enlargement and lengthening of the internal pipe. Figure 2.10 shows the mechanisms related to the cumulative effects in which backward erosion takes place.



**Fig. 2.10 A schematic diagram of underseepage mechanisms that contribute to cumulative effects both during a flood and immediately after a flood.**

Although there is no reported study emphasizing the cumulative effects in underseepage problems of levees, Turnbull and Mansur's study in 1961 implies the existence of cumulative effects. During the 1950 high water, upward gradients through the top stratum at some control sites were measured by piezometers. The gradient required to cause sand boils varied considerably at the different sites, possibly because at

sites where sand boils had developed previously only fairly low excess heads may have been needed to reactivate these boils in 1950. At sites where no sand boils had occurred in the past, higher gradients may have been required to initiate formation of the boils (Turnbull and Mansur, 1961). They also suggested that pressure relief resulting from the boil might have lowered piezometer readings in the area (Wolff, 2002). Currently, USACE Engineer Research and Development Center (ERDC) in Vicksburg, MS is working on research on cumulative effects of piping under levees as part of the Innovative Flood Damage Research Program (IFDR) sponsored by USACE (Wolff, 2002).

## **2.9 Summary and Concluding Remarks**

In the literature, seepage under levees associated with sand boils has been studied in detail. Qualitative and quantitative models exist to describe the mechanisms of seepage erosion. Geology of Lower Mississippi River Valley has also been well explored. Engineers should consider the complex geology in design of levees and underseepage analysis. As in all civil engineering problems, appropriate assumptions are required to solve confined flow problems. Overall, a variety of tools, design manuals, specifications and guidelines are successfully in use to perform a seepage analysis for levees. However, the literature depicts that transient flow conditions associated with sand boil problems have not been studied in detail in levee underseepage analysis.

As presented in Section 2.6, there are numerous analytical studies on transient flow and a variety of solution methods to the general one-dimensional flow equation (Equation 2.8) subject to fluctuating boundary conditions. However, there is relatively little information on relating these transient flow models to critical hydraulic gradients

and sand boil formation. In addition, as noted before, there is almost no information on the cumulative effects of seepage under levees and its relationship to piping.

Overall, the background and literature review presented in this chapter implies that the objectives set in this dissertation are important research topics. Successful completion of the research work would bring a new perspective to the problem.

## **2.10 List of Symbols and Acronyms**

$C$  = creep coefficient (dimensionless)

$C_c$  = coefficient of curvature (dimensionless)

$C_u$  = uniformity coefficient (dimensionless)

$C_w$  = weighted creep ratio (dimensionless)

$d$  = distance (L)

$d_{10}$  = grain diameter corresponding to 10% finer in grain size distribution curve (L)

$d_{30}$  = grain diameter corresponding to 30% finer in grain size distribution curve (L)

$d_{50}$  = grain diameter corresponding to 50% finer in grain size distribution curve (L)

$d_{60}$  = grain diameter corresponding to 60% finer in grain size distribution curve (L)

$e$  = void ratio of soil (dimensionless)

$\gamma_{\text{sub}}$  = submerged unit weight of soil ( $\text{WL}^{-3}$ )

$\gamma_w$  = unit weight of water ( $\text{WL}^{-3}$ )

$G_s$  = specific gravity of soil (dimensionless)

$h$  = hydraulic head (L)

$h$  = total head loss (L)

$h_x$  = head beneath top stratum at distance  $x$  from landside toe of the levee (L)

$i_c$  = critical hydraulic gradient (dimensionless)

$k_0$  = initial intrinsic permeability ( $\text{L}^2$ )

$L$  = length of seepage path (L)

$L_h$  = distance along horizontal contacts (L)

$L_v$  = distance along vertical contacts (L)

$n_0$  = initial porosity of soil (dimensionless)

$P$  = period of uniform fluctuations (T)

$S$  = aquifer storativity (dimensionless)

$t$  = time (T)

$t_{lag}$  = time lag (T)

$T$  = aquifer transmissivity ( $LT^{-2}$ )

$\tau_c$  = critical tractive shear stress ( $MT^{-2}L^{-1}$ )

$x$  = horizontal coordinate (L)

$z_t$  = thickness of landside top stratum

EM = Engineer Manual

ERDC = Engineer Research and Development Center

ETL = Engineer Technical Letter

GMS = Groundwater Modeling System

IFDR = Innovative Flood Damage Research Program

USACE = United States Army Corps of Engineers

WES = Waterways Experiment Station

TM = Technical Manual



## **CHAPTER 3      TRANSIENT FLOW MODEL IN A CONFINED AQUIFER**

### **3.1      Introduction**

The objective of this chapter was to develop analytical models that describe the hydraulic head in a confined aquifer on the landside of a levee system during the rising limb of a flood wave. One-dimensional linear-laminar saturated flow conditions in a homogenous, isotropic confined aquifer were studied. The top stratum is assumed as impervious. The models used a sinusoidally varying boundary condition to simulate the effects of the rising river stage. In these models, the governing equation is the diffusion equation that was developed under Darcy's law, and the law of conservation of mass (Freeze and Cherry, 1979). Darcy's law is valid as long as the Reynolds number based on grain diameter does not exceed some value between 1 to 10 (Bear, 1972).

Two solutions were presented. Section 3.2 details the development of the transient flow model by the Laplace transform method. Section 3.3 presents an approximate solution to the same problem. The analyses were extended to falling limb of a flood wave due to the fact that some field observations indicated critical situations during falling river stages (Section 2.3.1).

### **3.2      Analytical Modeling of Transient Hydraulic Head in a Confined Aquifer by Laplace Transform Method**

A schematic view of the model is shown in Fig. 3.1. The governing equation for a one-dimensional model of transient seepage through a confined aquifer is known as the diffusion equation (Freeze and Cherry, 1979)

$$\frac{\partial h_1}{\partial t} = \frac{T}{S} \frac{\partial^2 h_1}{\partial x^2} \quad (3.1)$$

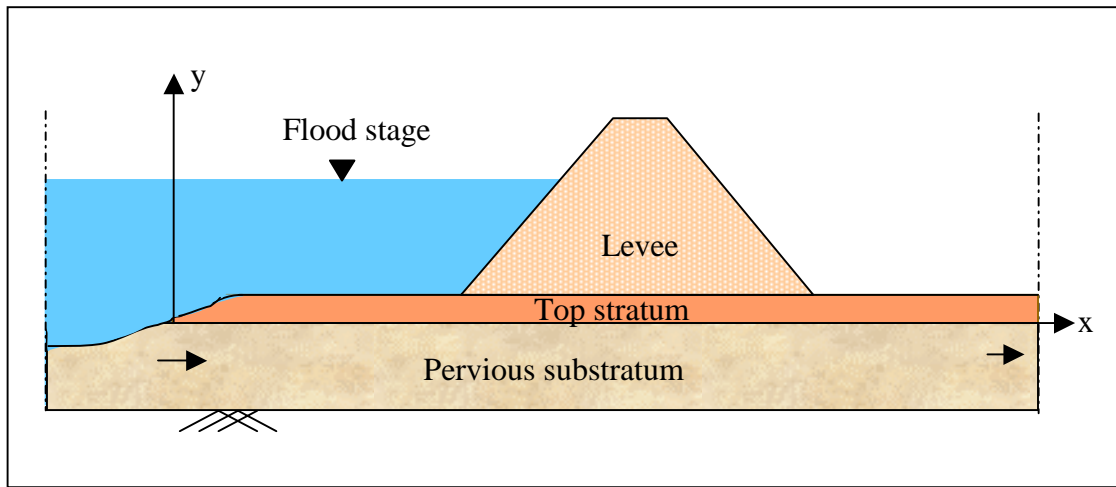
where  $h_l$  is the hydraulic head (L),  $T$  is the transmissivity ( $L^2/T$ ),  $t$  is time (T),  $S$  is the storativity, which is dimensionless and  $x$  is the distance from the entrance to the confined aquifer (L). The initial head at time  $t = 0$  is 0, assuming mean low river level is well below the origin which is the most common case. During high water, an initial head of  $H_0$  is developed. During the flood, fluctuation of this head is typical and defined as  $H_l \sin(\omega t)$  in the analysis. Another boundary condition is the head  $h = 0$  when  $x$  approaches infinity, which represents no influence of head far landward. Therefore, initial and boundary conditions are selected as

$$h_1(x, 0) = 0 \quad (3.2)$$

$$h_1(0, t) = H_0 + H_l \sin(\omega t) \quad (3.3)$$

$$\lim_{x \rightarrow \infty} h_1(x, t) \rightarrow 0 \quad (3.4)$$

where  $H_0$  is the initial hydraulic head applied to the aquifer,  $H_l$  is the amplitude of the variation from the initial hydraulic head and  $\omega$  is the frequency of the flood wave. To make the problem realistic  $H_0$  and  $H_l$  are positive or zero with the constraint that  $H_0 \geq H_l$ .



**Fig. 3.1 Schematic view of confined flow under a levee.**

The approach in setting up the governing equations is similar to the approach followed by Ozisik (1968) and Alshawabkeh and Adrian (1997). We define a new problem with dependent variable  $h_2(x, t)$  that is identical to Equations 3.1, 3.2, and 3.4 but the boundary condition is

$$h_2(0, t) = H_0 + H_1 \cos(\omega t) \quad (3.5)$$

Each term in the first problem is multiplied by the complex number  $i$  and is added to the second problem. Then, a new complex variable is introduced

$$h(x, t) = h_2(x, t) + ih_1(x, t) \quad (3.6)$$

where  $h_1(x, t)$ , the imaginary part of solution, satisfies the original problem Equations 3.1 to 3.4, and  $h_2(x, t)$ , the real part of the solution, satisfies the original problem with the boundary condition (Equation 3.3 changed to Equation 3.5).

The governing equation for the complex transient seepage becomes

$$\frac{\partial h}{\partial t} = \frac{T}{S} \frac{\partial^2 h}{\partial x^2} \quad (3.7)$$

$$h(x, 0) = 0 \quad (3.8)$$

$$h(0, t) = (1 + i)H_0 + H_1 \exp(i\omega t) \quad (3.9)$$

$$\lim_{x \rightarrow \infty} h(x, t) \rightarrow 0 \quad (3.10)$$

In Equation 3.9, Euler's relationship was used

$$\exp(i\omega t) = \cos(\omega t) + i \sin(\omega t) \quad (3.11)$$

The Laplace transform is applied to Equations 3.7 to 3.10 yielding

$$\frac{d^2 \bar{H}}{dx^2} - \frac{pS}{T} \bar{H} = 0 \quad (3.12)$$

$$\overline{H}(0) = \frac{1+i}{p} H_0 + \frac{H_1}{p-i\omega} \quad (3.13)$$

$$\lim_{x \rightarrow \infty} \overline{H}(x) \rightarrow 0 \quad (3.14)$$

where the term  $\overline{H}(x)$  is the Laplace transform of  $h(x,t)$  and  $p$  is the parameter in the transform. The solution to the Equation 3.12 subject to Equations 3.13 and 3.14 is

$$\overline{H}(x) = \left( \frac{1+i}{p} H_0 + \frac{H_1}{p-i\omega} \right) \exp\left(-x \sqrt{\frac{pS}{T}}\right) \quad (3.15)$$

The inverse Laplace transforms from Carslaw and Jaeger (1963) applicable to the Equation 3.15 in their original notation are

$$L^{-1}\left\{\frac{e^{-a\sqrt{p}}}{p}\right\} = \operatorname{erfc}\left(\frac{a}{2\sqrt{t}}\right) \quad (3.16)$$

$$L^{-1}\left\{\frac{e^{-a\sqrt{p}}}{p-\omega}\right\} = \frac{1}{2} e^{\omega t} \left[ e^{-a\sqrt{\omega}} \operatorname{erfc}\left(\frac{a}{2\sqrt{t}} - \sqrt{\omega t}\right) + e^{a\sqrt{\omega}} \operatorname{erfc}\left(\frac{a}{2\sqrt{t}} + \sqrt{\omega t}\right) \right] \quad (3.17)$$

When the inverse transform is applied to the Equation 3.15, the solution becomes

$$h(x,t) = (1+i)H_0 \operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}\right) + \frac{1}{2} H_1 \exp(i\omega t) \left[ \exp\left(-x \sqrt{\frac{iS\omega}{T}}\right) \operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{i\omega t}\right) + \exp\left(x \sqrt{\frac{iS\omega}{T}}\right) \operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{i\omega t}\right) \right] \quad (3.18)$$

Equation 3.18 should be separated into its real and imaginary parts to be applicable to practical problems. The treatment of the real and imaginary parts of the complex function (Equation 3.18) is the same as the procedure of Fourier as cited by Tikhonov and Samarskii (1963). Separation of the expression

$$E(x,t) = \frac{1}{2} H_1 \exp(i\omega t) \left[ \begin{array}{l} \exp\left(-x\sqrt{\frac{iS\omega}{T}}\right) \operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{i\omega t}\right) + \\ \exp\left(x\sqrt{\frac{iS\omega}{T}}\right) \operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{i\omega t}\right) \end{array} \right] \quad (3.19)$$

from Equation 3.18 into its real and imaginary parts is discussed term by term. By

applying Equation 3.11

$$\exp\left(\mp x\sqrt{\frac{iS\omega}{T}}\right) = \exp\left(\mp \sqrt{\frac{Sr}{T}} \cos \frac{\theta}{2}\right) \left\{ \cos\left(x\sqrt{\frac{Sr}{T}} \sin \frac{\theta}{2}\right) + i \sin\left(\mp \sqrt{\frac{Sr}{T}} \sin \frac{\theta}{2}\right) \right\} \quad (3.20)$$

where  $r=\omega$  and  $\theta=\pi/2$ .

Next, the complementary error function can be expanded as (Abramowitz and Stegun, 1965)

$$\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{i\omega t}\right) = \operatorname{erfc}(R1 + iI1) \quad (3.21)$$

$$\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{i\omega t}\right) = \operatorname{erfc}(R2 + iI2) \quad (3.22)$$

where

$$R1 = \frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{rt} \cos \frac{\theta}{2} \quad (3.23)$$

$$R2 = \frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{rt} \cos \frac{\theta}{2} \quad (3.24)$$

$$I1 = -\sqrt{rt} \sin \frac{\theta}{2} \quad (3.25)$$

$$I2 = \sqrt{rt} \sin \frac{\theta}{2} \quad (3.26)$$

where  $r$  and  $\theta$  were defined in Equation 3.20.

To evaluate the complementary error function of a complex number, the following approximation is used (Abramowitz and Stegun, 1965):

$$\operatorname{erf}(R + iI) = F(R, I) + iG(R, I) + \varepsilon(R, I) \quad (3.27)$$

where  $\operatorname{erfc}(y) = 1 - \operatorname{erf}(y)$ , and

$$F(R, I) = \operatorname{erf}(R) + \frac{\exp(-R^2)}{2\pi R} (1 - \cos(2RI)) + \frac{2}{\pi} \exp(-R^2) \sum_{n=1}^{\infty} \frac{\exp(-n^2/4)}{n^2 + 4R^2} f_n(R, I) \quad (3.28)$$

$$G(R, I) = \frac{\exp(-R^2)}{2\pi R} \sin(2RI) + \frac{2}{\pi} \exp(-R^2) \sum_{n=1}^{\infty} \frac{\exp(-n^2/4)}{n^2 + 4R^2} g_n(R, I) \quad (3.29)$$

$$f_n(R, I) = 2R - 2R \cosh(nI) \cos(2RI) + n \sinh(nI) \sin(2RI) \quad (3.30)$$

$$g_n(R, I) = 2R \cosh(nI) \sin(2RI) + n \sinh(nI) \cos(2RI) \quad (3.31)$$

and

$$\varepsilon \approx 10^{-16} |\operatorname{erf}(R + iI)| \quad (3.32)$$

As  $\varepsilon \approx 10^{-16} |\operatorname{erf}(R + iI)|$ , negligible error is introduced into the calculations when using Equation 3.27. Now Equation 3.12 can be separated into the portion applicable to the sine boundary condition, Equation 3.3 and cosine boundary condition, Equation 3.5. The solution applicable for the sine boundary condition is

$$h_1(x, t) = H_0 \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{Tt}}\right) + \operatorname{Im}\{h(x, t)\} \quad (3.33)$$

Equation 3.33 is the solution to the problem introduced in Equations 3.1 through 3.4

where  $\operatorname{Im}\{h(x, t)\}$  is the imaginary part of  $h(x, t)$

$$\begin{aligned}
\text{Im}\{h_1(x,t)\} = \frac{1}{2}H_1 \cos(\omega t) & \left\{ \exp\left(-x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & -\cos\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)G(R1,I1) \\ & + \sin\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1)) \end{aligned} \right] + \right. \\
& \left. \exp\left(x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & -\cos\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)G(R2,I2) \\ & + \sin\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2)) \end{aligned} \right] \right\} \\
+ \frac{1}{2}H_1 \sin(\omega t) & \left\{ \exp\left(-x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & \cos\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1)) \\ & + \sin\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)G(R1,I1) \end{aligned} \right] + \right. \\
& \left. \exp\left(x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & \cos\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2)) \\ & + \sin\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right)G(R2,I2) \end{aligned} \right] \right\} \quad (3.34)
\end{aligned}$$

This solution is applicable to determine time-dependent hydraulic head development beneath the levee as a response to the stage fluctuations observed in the river.

Similarly, the solution to the problem with cosine boundary equations, Equations 3.1, 3.2, 3.4 and 3.6, is

$$h_2(x,t) = H_0 \text{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}\right) + \text{Re}\{h(x,t)\} \quad (3.35)$$

where  $\text{Re}\{h(x,t)\}$  is the real part of  $h(x,t)$

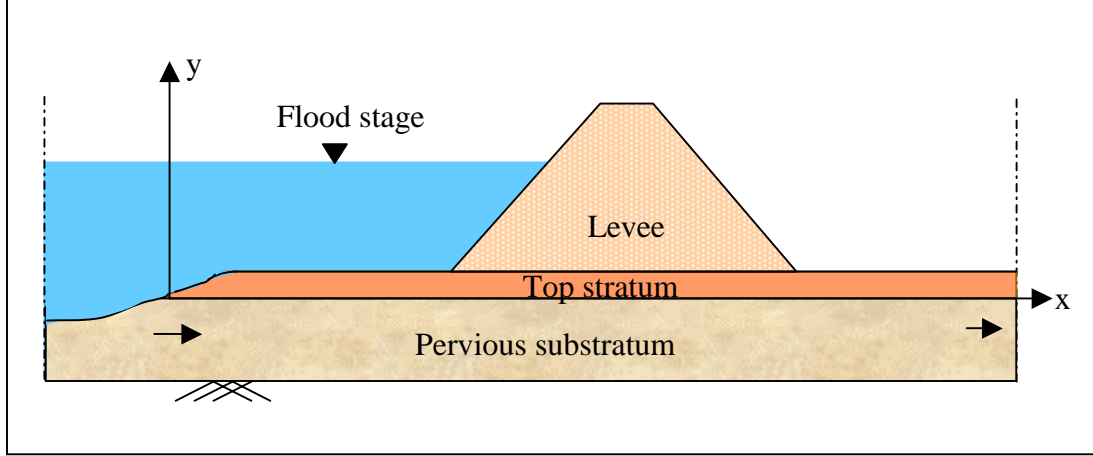
$$\begin{aligned}
\text{Re}\{h_2(x,t)\} = & \frac{1}{2} H_1 \cos(\omega t) \left\{ \exp\left(-x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) (1-F(R1,I1)) \right. \right. \\
& \left. \left. + \sin\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) G(R1,I1) \right] + \right. \\
& \left. \exp\left(x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) (1-F(R2,I2)) \right. \right. \\
& \left. \left. + \sin\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) G(R2,I2) \right] \right\} \\
& - \frac{1}{2} H_1 \sin(\omega t) \left\{ \exp\left(-x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) G(R1,I1) \right. \right. \\
& \left. \left. + \sin\left(-x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) (1-F(R1,I1)) \right] + \right. \\
& \left. \exp\left(x\sqrt{\frac{Sr}{T}} \cos\left(\frac{\theta}{2}\right)\right) \left[ -\cos\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) G(R2,I2) \right. \right. \\
& \left. \left. + \sin\left(x\sqrt{\frac{Sr}{T}} \sin\left(\frac{\theta}{2}\right)\right) (1-F(R2,I2)) \right] \right\}
\end{aligned} \tag{3.36}$$

Although the solution can be evaluated by a mathematics software, it is a long and complex solution. Therefore, an approximate solution method to the same problem was studied and will be presented in the next section.

### 3.3 Analytical Modeling of Transient Hydraulic Head in a Confined Aquifer by an Approximate Method

Jiao and Tang (1999) presented an approximate solution to a problem of groundwater response to tidal fluctuation in a leaky confined aquifer. This solution follows their method for an approximate transient seepage model in a confined aquifer. A schematic view of the model is shown in Fig. 3.2.





**Fig. 3.2 A schematic view of confined flow under a levee for an approximate solution.**

The governing equation for confined flow with initial and boundary conditions are

$$\frac{\partial h}{\partial t} = \frac{T}{S} \frac{\partial^2 h}{\partial x^2} \quad (3.37)$$

$$h(x,0) = h_0 \quad (3.38)$$

$$h(0,t) = h_0 + h_1 \sin(\omega t) \quad (3.39)$$

$$\lim_{x \rightarrow \infty} h(x,t) = h_0 \quad (3.40)$$

Let  $H = h - h_0$ , then the differential equation becomes as follows with initial and boundary conditions:

$$\frac{\partial H}{\partial t} = \frac{T}{S} \frac{\partial^2 H}{\partial x^2} \quad (3.41)$$

$$H(x,0) = 0 \quad (3.42)$$

$$H(0,t) = h_1 \sin(\omega t) \quad (3.43)$$

$$\lim_{x \rightarrow \infty} H(x,t) = 0 \quad (3.44)$$

Equation 3.43 is in the form of  $H(0,t) = h_1 \text{Im} e^{i(\omega t)}$ , then the solution can be assumed as:

$$H(x,t) = h_1 e^{\lambda x} e^{i(\omega t)} \quad (3.45)$$

Substitute the solution in Equation 3.41,

$$\lambda^2 = \frac{i\omega S}{T} \quad (3.46)$$

Let  $\lambda = -p + iq$ , then

$$p = \sqrt{\frac{\omega S}{2T}} \quad (3.47)$$

$$q = -\frac{\omega S}{2pT} \quad (3.48)$$

$$H(x,t) = H_1 \text{Im}[e^{-px} e^{i(\omega t + qx)}] \quad (3.49)$$

$$H(x,t) = h_1 e^{-px} \sin(\omega t + qx) \quad (3.50)$$

Back to the original problem

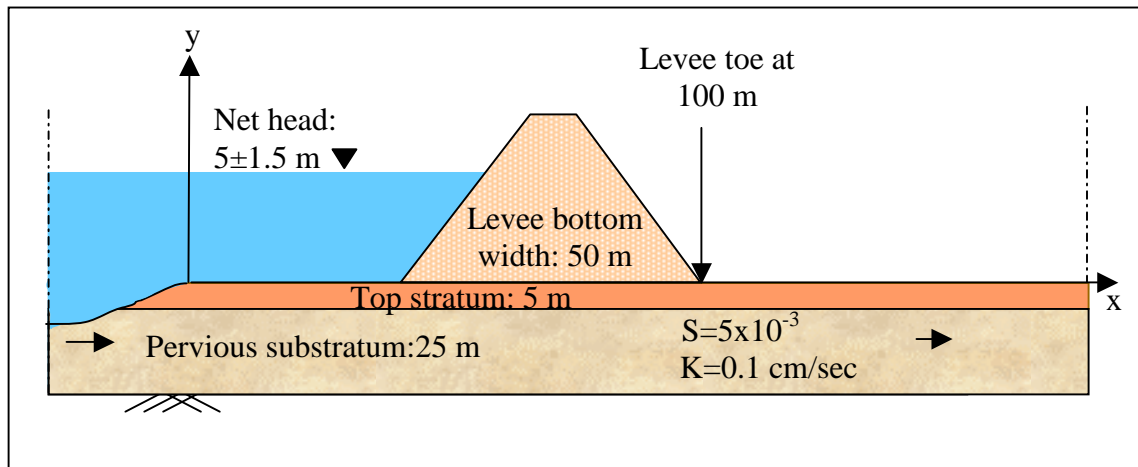
$$h(x,t) = h_0 + h_1 e^{-px} \sin\left(\omega t - \frac{\omega S}{2pT} x\right) \quad (3.51)$$

So, an approximate solution was found to the problem defined in Equations 3.37 through 3.40. This is an approximate solution because the final solution was initially assumed as shown in Equation 3.45. Also, the final solution, Equation 3.51, does not satisfy the initial condition specified in Equation 3.38. Thus, Equation 3.51 is called a quasi steady-state solution, which is applicable, when time is large enough that the initial condition is forgotten.

### 3.4 Results and Discussion

A typical levee section defined by the Army Corps is selected for analysis purpose (EM 1110-2-1913). The thickness of sandy alluvium under Mississippi River levees varies from 25 m to 45 m. The thickness of low permeable top layer under Mississippi

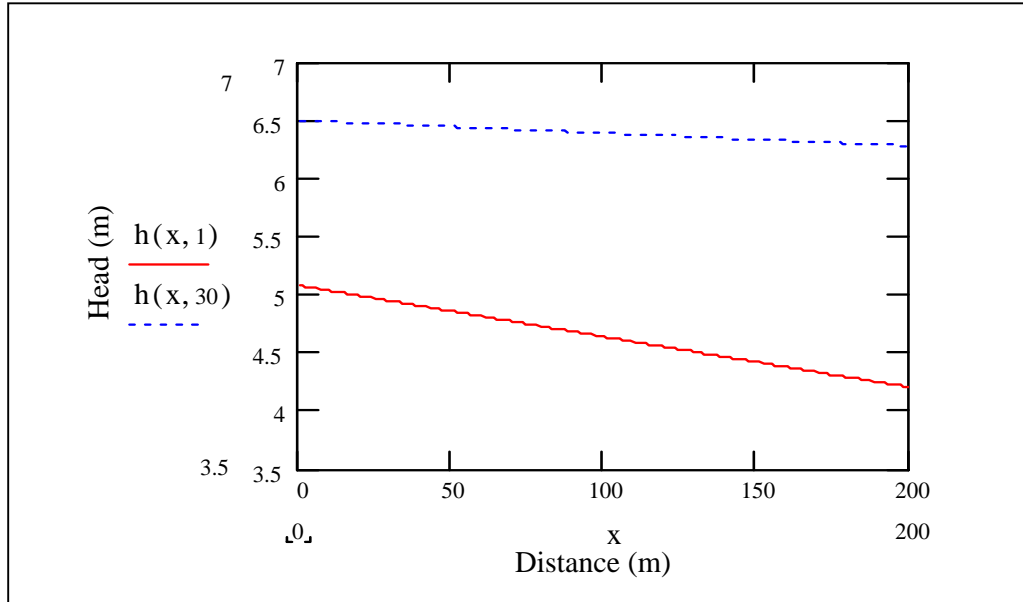
River levees ranges from 1.5 m to 37.5 m. The hydraulic conductivity of sandy alluvium ranges from 0.1 cm/sec to 0.2 cm/sec (Turnbull and Mansur, 1961). Typical storativity values for confined aquifers are  $5 \times 10^{-3}$ ,  $5 \times 10^{-4}$ ,  $5 \times 10^{-5}$  (Freeze and Cherry, 1979). In the 1993 floods, the net river level elevation change of the middle Mississippi River levees was recorded as 4.8 to 6.7 m (Mansur *et al.* 2000). A net head of 5 m and a fluctuation of 1.5 m were selected in the analysis. The typical levee section with selected aquifer parameters and hydraulic head is shown in Fig. 3.3.



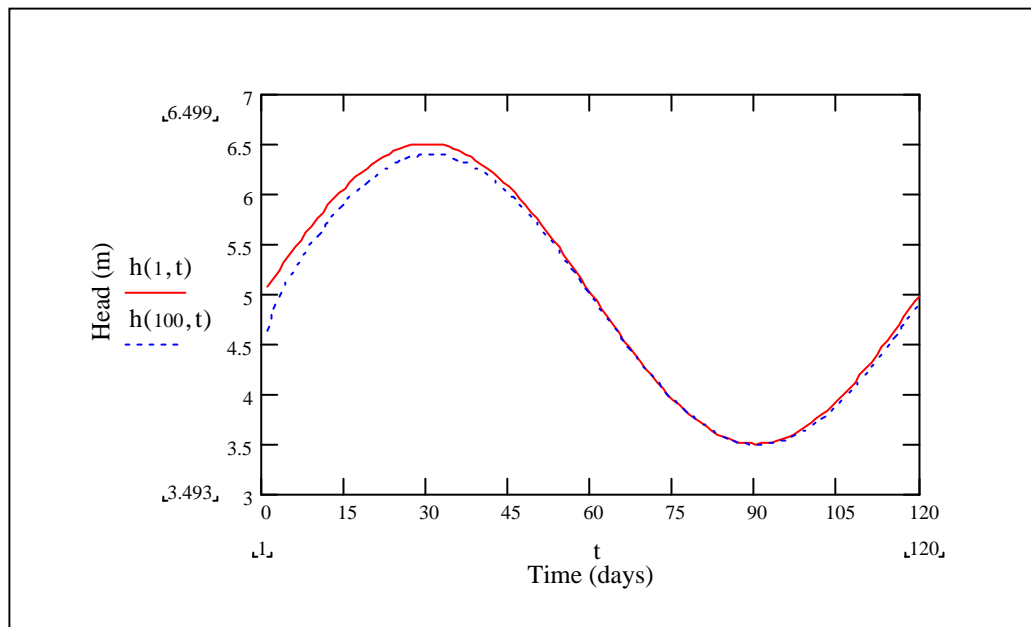
**Fig. 3.3 A typical levee section with selected parameters (not in scale).**

The flood duration was selected as 60 days. The net head starts at 5 m, rises to the peak of 6.5 m at time=30 days, and falls back to 5 m at time=60 days. Head development over a distance of 200 m was determined, which included 50 m at riverside, a 50 m levee base, and 100 m on the landside of the levee. The analysis was restricted to 100-m landside of the levee because, as noted in the literature review, Li *et al.*(1996) reported that there was no significant evidence of surface seepage beyond 100 m from the levee north of Cairo, Illinois after the 1993 high water. The exit gradient at the levee toe and landside of the levee was also calculated by taking the difference between the heads above and below the top stratum and dividing by the top stratum thickness. Calculations

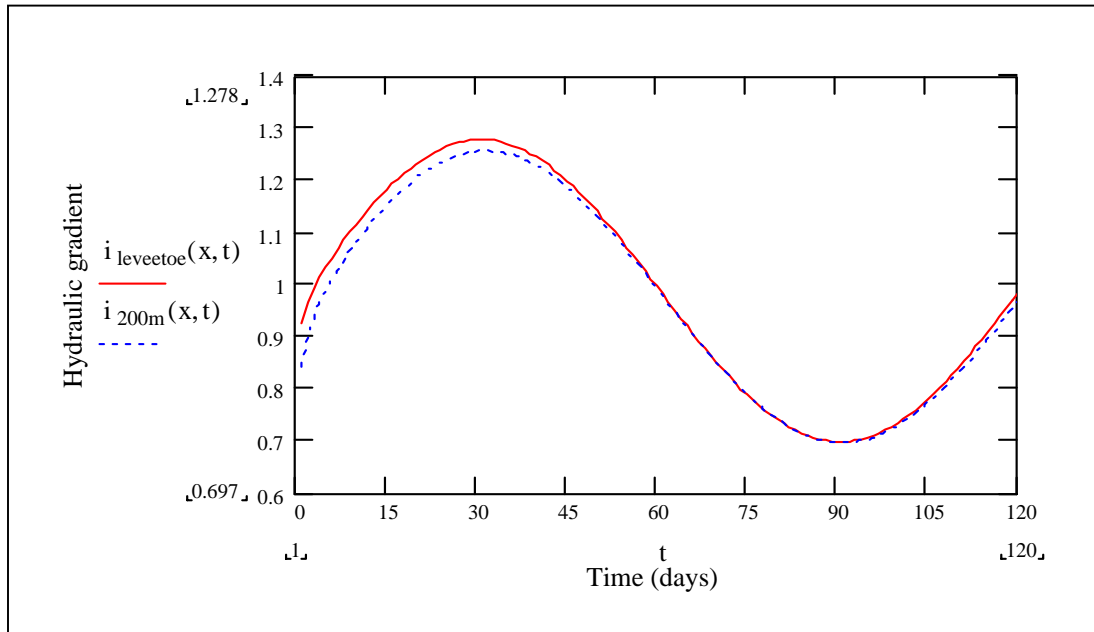
were performed by MathCad 2000 software. Figures 3.4, 3.5, 3.6 and 3.7 show the results by the Laplace transform method. Figures 3.8, 3.9, 3.10 and 3.11 show the results by the approximate method.



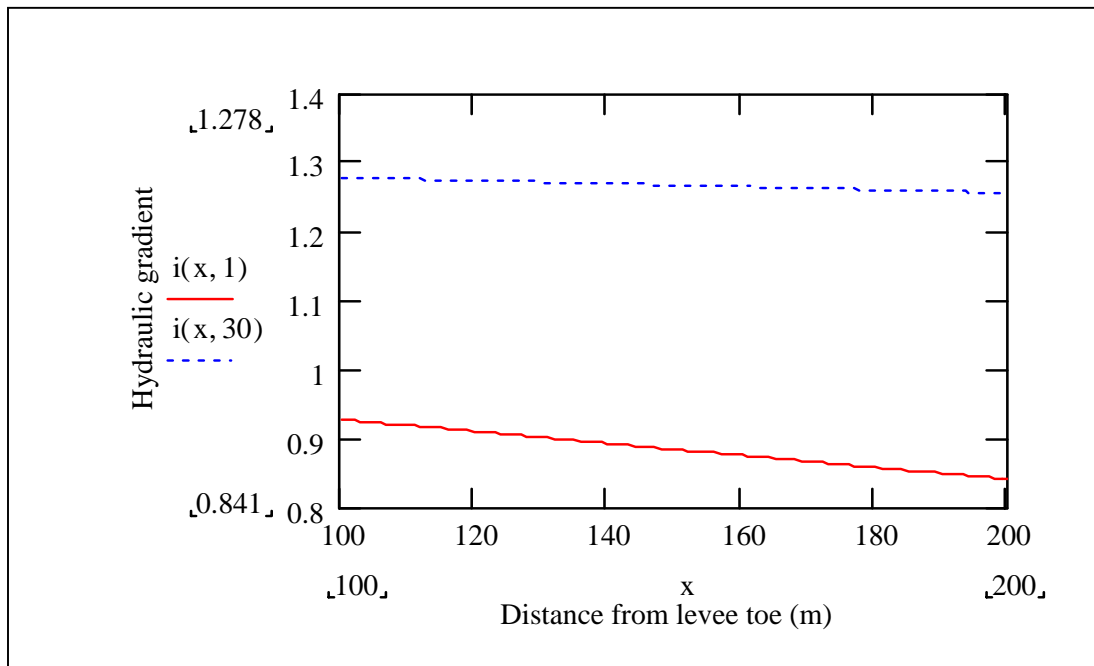
**Fig. 3.4 Transient head development at  $t=1$  day and 30 days by Laplace transform method.**



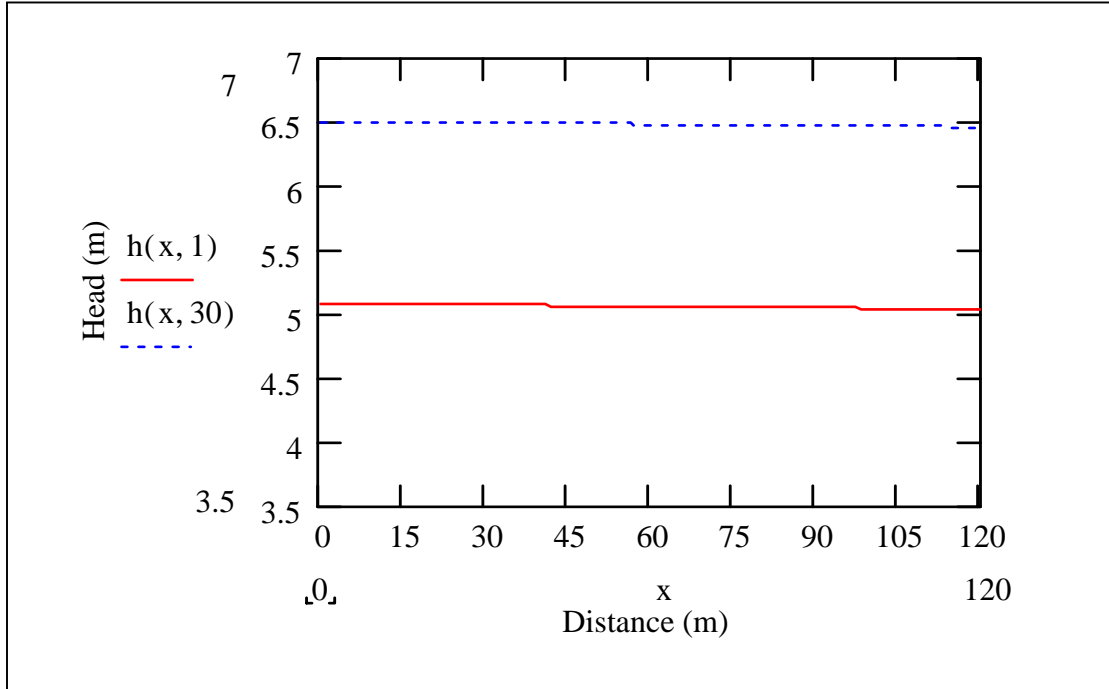
**Fig. 3.5 Transient head development at  $x=1$  m and  $x=100$  m, levee toe, by Laplace transform method.**



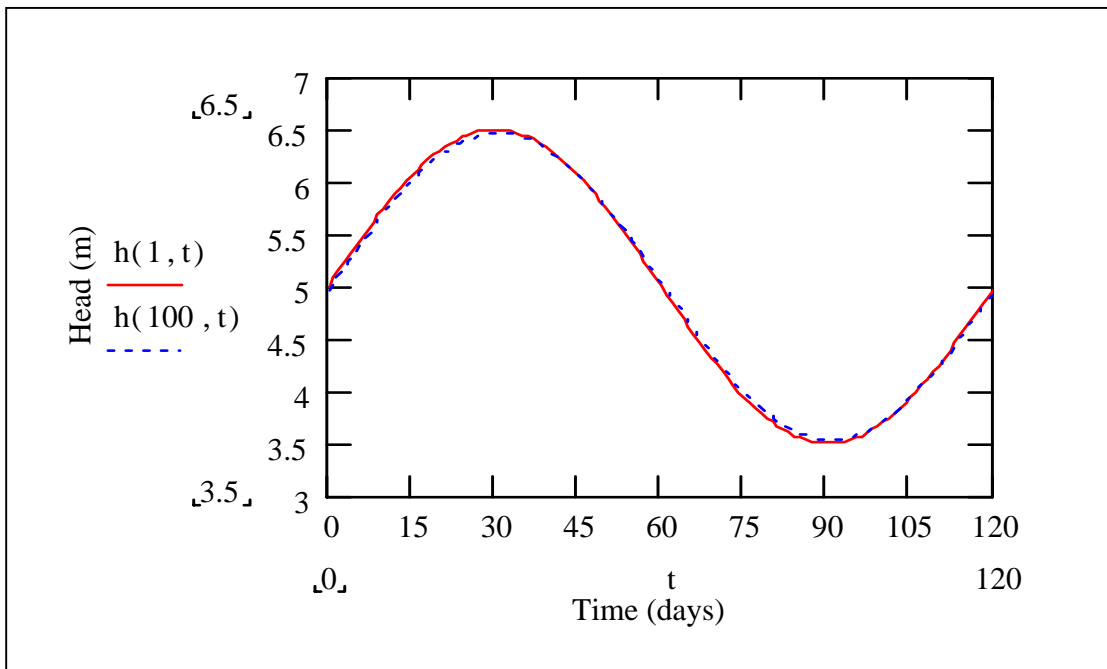
**Fig. 3.6 Transient exit gradient at the levee toe and at 200-m landside of levee by Laplace transform method.**



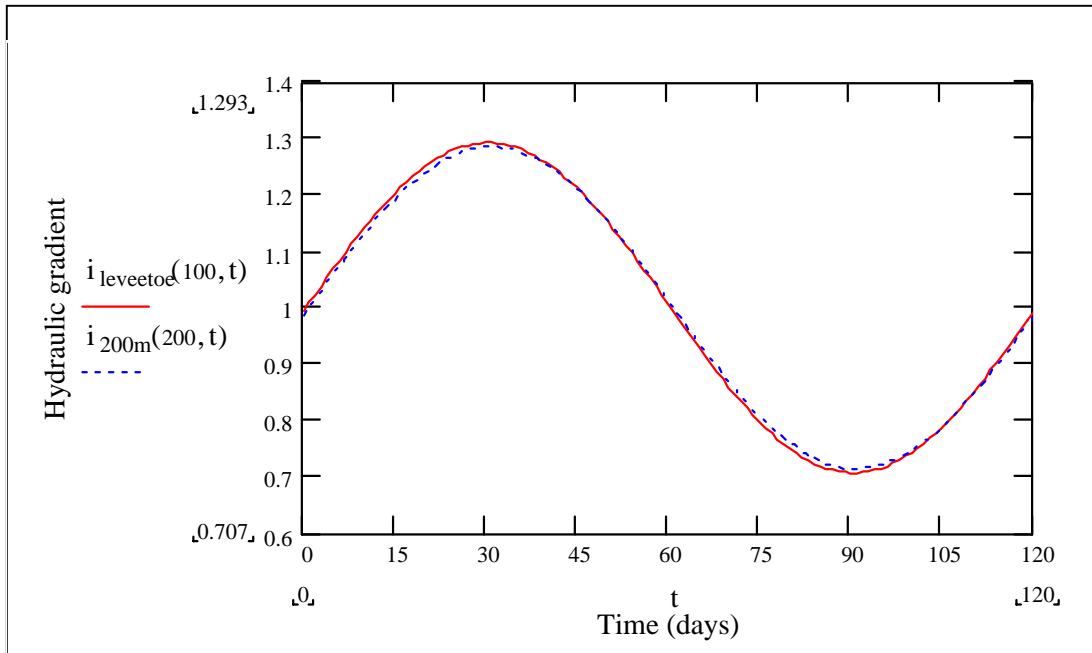
**Fig. 3.7 Transient exit gradient at  $t=1$  day and  $t=30$  days at landside of the levee by Laplace transform method.**



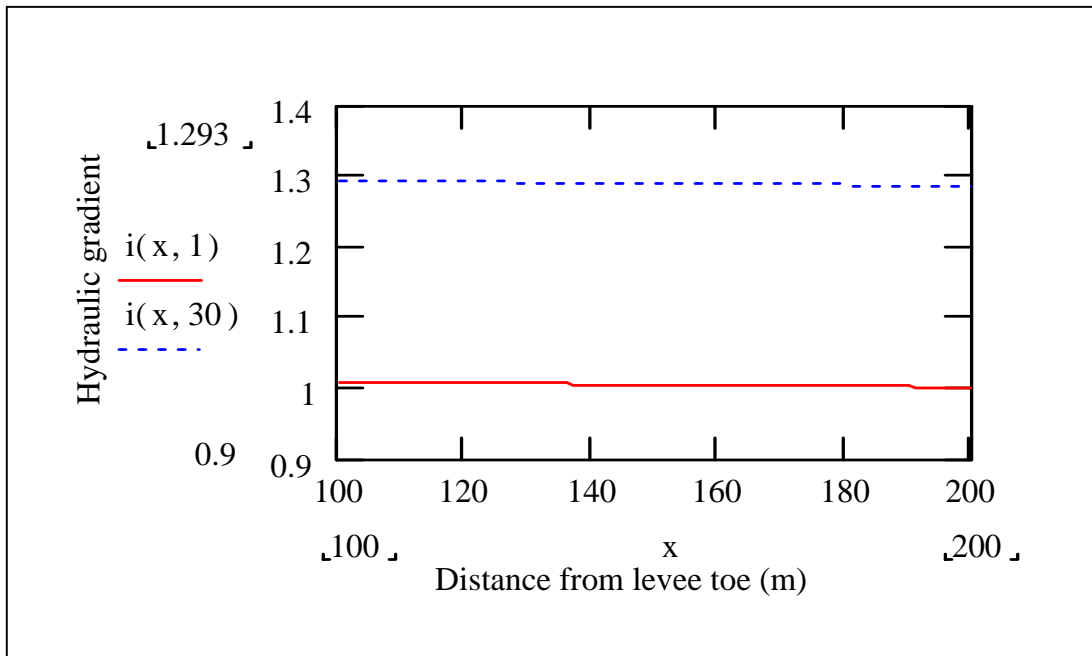
**Fig. 3.8 Transient head development at  $t=1$  day and  $t=30$  days by the approximate method.**



**Fig. 3.9 Transient head development at  $x=1$  m and  $x=100$  m, levee toe, by the approximate method.**



**Fig. 3.10 Transient exit gradient at the levee toe and at 200-m landside of the levee by the approximate method.**



**Fig. 3.11 Transient exit gradient at  $t=1$  day and  $t=30$  days at landside of the levee by the approximate method.**

In general, both solutions give the expected 1.5 m sinusoidal head fluctuation with an initial head of 5 m, with a peak at 30 days, and the part of the graphs after 30 days represents the falling river stage (Figures 3.5 and 3.9). The approximate method performs well compared with Laplace transform solution. Both solutions give minor head dissipation with distance. Hydraulic head dissipates more rapidly at 100 m farther from the levee toe by Laplace transform solution than by the approximate solution. Both solutions assume a horizontal flow in semi-infinite layer. This assumption may be the reason for minor head dissipations with distance. Table 1.1 shows the summary of the results.

**Table 3.1 Summary of the results by Laplace transform method and the approximate solution.**

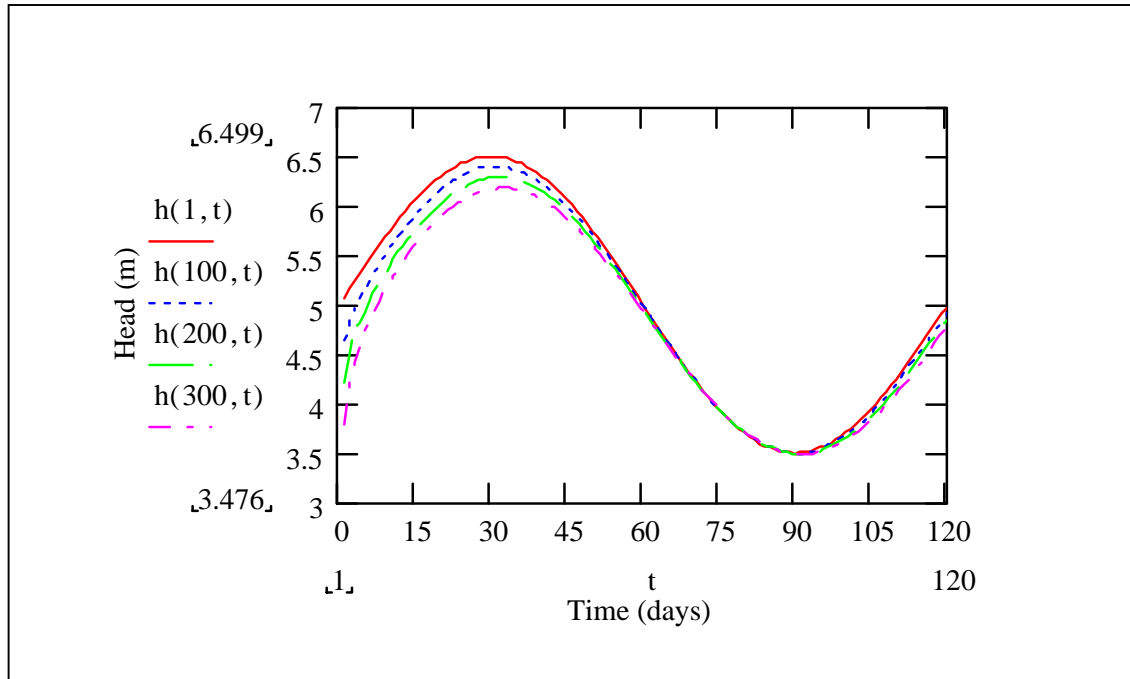
Head (m) and Hydraulic gradient	Time (day)	Laplace transform Method	Approximate Method
Head at levee toe (m)	1	4.64	5.04
	30	6.39	6.46
Head at 100 m farther than levee toe (m)	1	4.20	5.00
	30	6.28	6.43
Hydraulic gradient at levee toe	1	0.93	1.01
	30	1.28	1.30
Hydraulic gradient at 100 m farther than levee toe	1	0.84	1.00
	30	1.26	1.29

#### Time Lag in Head Development

One interesting common behavior is that both solutions show only a minor time lag between the peak points of sinusoidal head curves with distance. In other words, the peaks of head wave by Laplace transform solution (Fig. 3.5) and by the approximate



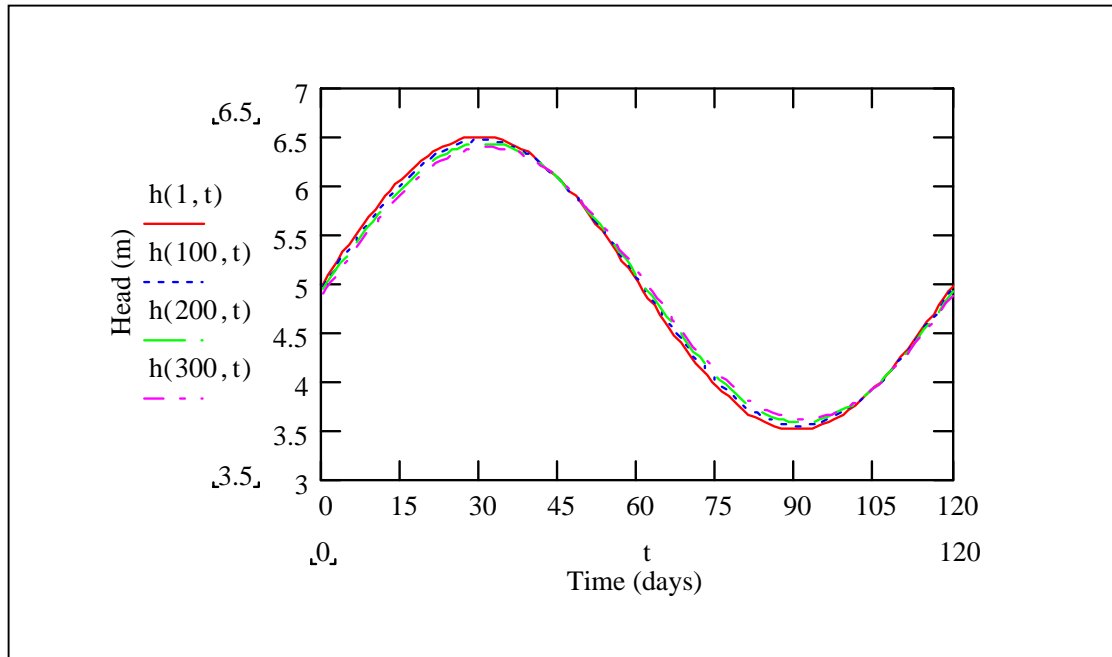
solution (Fig. 3.9) correspond to about 30 days at the levee toe and also at 100 m farther than the levee toe. Based on Meehan's observations of levee failure on the Feather River, California, during the falling river stage in 1986 (reported in Chapter 2), one would expect to observe a time lag between the peak points of the head waves at varying distances. Figures 3.12 and 3.13 explore more on this subject.



**Fig. 3.12 Transient head development beneath the levee at various distances from the river by Laplace transform method.**

The time of occurrence of the peak points of the river hydrograph and the peak hydraulic head of each head wave at various distances by Laplace transform and the approximate method are also summarized in Table 3.2.

Both solution methods show a minor time difference between the peak heads at various distances. As presented in Chapter 2, Ferris (1951) developed analytical expressions to determine the aquifer diffusivity ( $T/S$ ) based on the observed values of amplitude, lag, velocity, and wavelength of the sinusoidal changes in groundwater level.



**Fig. 3.13 Transient head development beneath the levee at various distances from the river by the approximate method.**

**Table 3.2 Time of occurrence of the peak points of head wave at variable distances.**

Methods	Time and Head at peak	x=1 m	x=100m (levee toe)	x=200 m	x=300 m
Laplace Transform Method	Time (days)	30	31	31	32
	Head (m)	6.50	6.39	6.28	6.18
Approximate Method	Time (days)	30	30	31	31
	Head (m)	6.50	6.46	6.43	6.39

If the time lag between surface and groundwater maximum and minimum stages is known, then the aquifer diffusivity can be estimated by using the following formula (EM 1110-2-1421, Equation 6-9):

$$t_{lag} = d \sqrt{\frac{PS}{4\pi T}} \quad (3.52)$$

where  $t_{lag}$  is the lag time in the occurrence of the maximum groundwater stage following the occurrence of a similar surface stage,  $d$  is the distance from an observation well to the

surface water, and  $P$  is the period of uniform tide or stage fluctuations. Equation 3.52 can be applied to time lag analysis of transient head development due to river fluctuations. If the same parameters as in the time lag analysis ( $d = 100$  m,  $P = 60$  days,  $S = 0.005$ ,  $T = 2160$  m<sup>2</sup>/day) of Laplace transform and approximate methods were applied to Equation 3.52, the time lag would result in 0.33 days for every 100-m of distance.

Only field studies can confirm the reliability of time lags estimated by the transient flow models. As noted in the literature review, a levee collapse near Marysville, California, occurred one day after the peak of the flood stage of Feather River. Part of the time delay may have been due to the time required for sand boils to erode channels or pipes under the levee, undermine it, and accelerate its failure. At Louisiana State University Dairy Farm, however, an existing sand boil was reported to have responded very quickly with the river stage fluctuations.

Base on limited field studies and an analytical estimation, the time lag results presented in Table 1.2 appear to be reasonable.

### **3.5 Summary**

Two transient flow models were developed to describe the hydraulic head development beneath the landside levee in response to head fluctuations in the river. The rising river stage was defined by a sinusoidally varying boundary condition. Both models consider one-dimensional saturated flow conditions in a homogenous isotropic confined aquifer. The first transient flow model was developed by solving the governing diffusion equation and the boundary conditions (Equation 3.1 through 3.4) by Laplace transform method. This solution method is complicated and can be evaluated only by a

mathematical software. Therefore, an approximate solution was also presented. The results were evaluated for a typical levee section.

Both solutions result in expected head fluctuations. The approximate solution performs well compared with the Laplace transform method. Both solutions give minor head dissipation with time and distance. Both solutions also result in minor time lag between the peak points of head waves at various distances. The distinctions between the two solutions would become more apparent if the period of the river hydrograph decreased, and if the development of heads and gradients at small times was sought. Then the Laplace transform solution's performance would be enhanced over the performance of the approximate method.

The main objective of this chapter was to develop transient flow models by the Laplace transform method and by an approximate method. This objective was satisfied. The applicability and performance analysis of these flow models will be studied in the following chapters.

### **3.6 List of Symbols**

$a$  = constant in inverse Laplace transform

$d$  = distance (L)

$E(x, t)$  = an expression for a part of the hydraulic head function

$f_n$  = function used to calculate error function

$F$  = real function used to calculate an error function

$g_n$  = function used to calculate error function

$\varepsilon$  = error of approximation

$G$  = imaginary function used to calculate an error function

$h$  = hydraulic head (L)

$h(x, t)$  = hydraulic head function

$h_1(x, t)$  = imaginary part of hydraulic head function

$h_2(x, t)$  = real part of hydraulic head function

$h_0$  = initial hydraulic head (L)

$H_0$  = initial hydraulic head (L)

$h_1$  = amplitude of the variation from the initial hydraulic head (L)

$H_1$  = amplitude of the variation from the initial hydraulic head (L)

$\overline{H}(x, t)$  = Laplace transform of  $h(x, t)$

$i$  = imaginary unit where  $i^2 = -1$

$I_1, I_2$  = imaginary part of a complex variable

$n$  = index of summation

$\lambda$  = a complex variable

$p$  = real part of the complex variable  $\lambda$

$p$  = complex number in Laplace transform

$P$  = period of uniform stage fluctuations (T)

$r$  = inverse of length squared ( $L^{-2}$ )

$q$  = imaginary part of the complex variable  $\lambda$

$R_1, R_2$  = real part of a complex variable

$S$  = aquifer storativity (dimensionless)

$t$  = time (T)

$t_{lag}$  = time lag (T)

$T$  = aquifer transmissivity ( $LT^{-2}$ ), also time dimension

$x$  = horizontal coordinate (L)

$y$  = variable in error function

$z_t$  = thickness of landside top stratum (L)

$\theta$  = phase angle for frequency ratio

$\omega$  = frequency of the flood wave ( $T^{-1}$ )

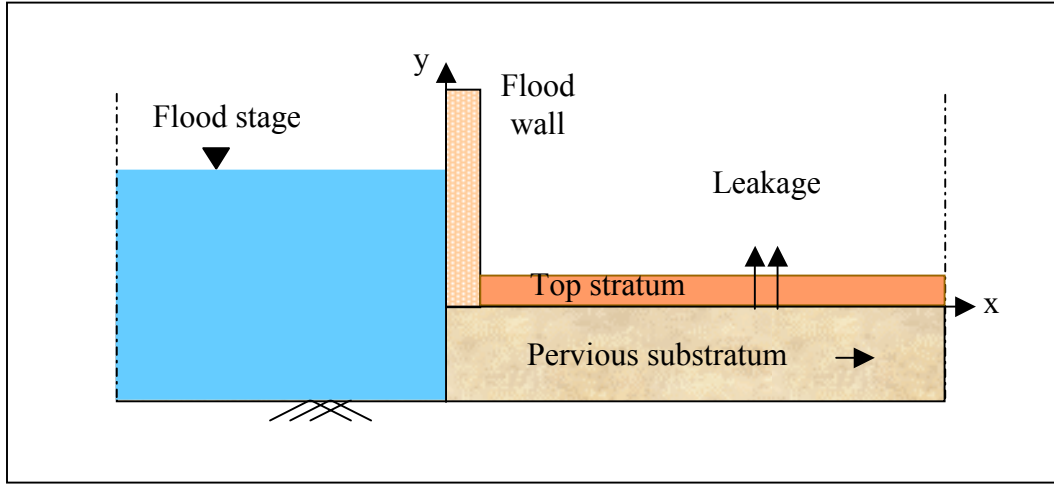
## **CHAPTER 4     TRANSIENT FLOW MODEL WITH LEAKAGE OUT OF A CONFINED AQUIFER**

### **4.1     Introduction**

The objective of this chapter was to modify the analytical flow models developed in the previous chapter by considering leakage occurring out of the confined aquifer. This condition simulates the occurrence of loss of water by upward seepage and discharge through sand boils at the landside of a levee or a flood wall system. The sand boils develop at random points landside of the levee. The solution methods presented here describe a homogenous leakage out of a confined aquifer through the landside of a levee or a flood wall. The system considered is a subsurface confined aquifer with one-dimensional saturated flow and semi-permeable layer on top. The aquifer is assumed to be homogenous and isotropic. The models used a sinusoidally varying boundary condition to simulate the effects of the rising river stage. In these models, the governing equation is the diffusion equation that was developed under Darcy's law, and the law of conservation of mass. Two solutions were presented. The first solution used Laplace transform method and followed the same methodology outlined in Section 3.2. The second solution is an approximate solution and the same methodology outlined in Section 3.3 was followed. The analyses were extended to the falling limb of a flood wave due to the fact that some field observations indicated critical situations during the falling river stages (Section 2.3.1).

### **4.2     Analytical Modeling of Transient Hydraulic Head with Leakage Out of a Confined Aquifer by Laplace Transform Method**

The model was set up considering a subsurface system with a leaky confined aquifer, and a semi-permeable layer on top representing the blanket layer (Fig. 4.1).



**Fig. 4.1 Schematic view of confined flow under a flood wall with leakage out of an aquifer.**

The initial head at time  $t = 0$  is 0; assuming mean low river level is well below the origin which is the most common case. During high water, an initial head of  $h_0$  is developed. The fluctuation of this head is typical and defined as  $h_1 \sin(\omega t)$  in the analysis. Another boundary condition is the head  $h = 0$  when  $x$  approaches infinity which represents a condition in which there is no influence of head far landward. Under these conditions, the governing equation is:

$$\frac{\partial h}{\partial t} = \frac{T}{S} \frac{\partial^2 h}{\partial x^2} - \frac{L}{S} h \quad (4.1)$$

where  $h$  is the hydraulic head,  $T$  is the transmissivity,  $t$  is time,  $S$  is the storativity,  $L$  is the leakage, and  $x$  is the distance from the entrance to the confined aquifer. The initial and boundary conditions may be given as

$$h(x, 0) = 0 \quad (4.2)$$

$$h(0, t) = h_0 + h_1 \sin(\omega t) \quad (4.3)$$

$$\lim_{x \rightarrow \infty} h(x, t) \rightarrow 0 \quad (4.4)$$



where  $h_0$  is the initial hydraulic head applied to the aquifer,  $h_l$  is the amplitude of the variation from the initial hydraulic head and  $\omega$  is the frequency of the flood wave,  $\omega = 2\pi/P$ , where  $P$  is the fluctuation period. To make the problem realistic  $h_0$  and  $h_l$  are positive or zero with the constraint that  $h_0 \geq h_l$ . The leakage,  $L$  is the ratio of hydraulic conductivity of the semi-confining layer to the thickness of semi-confining layer. We apply the transform  $h(x, t) = Y(x, t) \exp(-L t/S)$  to Equations 4.1 to 4.4 get a homogenous differential equation. The new set of equations becomes

$$\frac{\partial Y}{\partial t} = \frac{T}{S} \frac{\partial^2 Y}{\partial x^2} \quad (4.5)$$

$$Y(x, 0) = 0 \quad (4.6)$$

$$Y(0, t) = h_0 \exp\left(\frac{L}{S} t\right) + h_l \sin(\omega t) \exp\left(\frac{L}{S} t\right) \quad (4.7)$$

$$\lim_{x \rightarrow \infty} Y(x, t) = 0 \quad (4.8)$$

Now an approach similar to one followed by Ozisik (1968), and Alshawabkeh and Adrian (1997) and outlined in Section 3.2 is followed. A new problem is defined with dependent variable  $Z(x, t)$  that is identical to Equations 4.5, 4.6, and 4.8 but the boundary condition is

$$Z(0, t) = h_0 \exp\left(\frac{L}{S} t\right) + h_l \cos(\omega t) \exp\left(\frac{L}{S} t\right) \quad (9)$$

Each term in the first problem is multiplied by the complex number  $i$  where  $i = \sqrt{-1}$ , and the two problems are superimposed. Then, a new complex variable is introduced

$$\tilde{H}(x, t) = Z(x, t) + iY(x, t) \quad (10)$$

where  $Y(x,t)$ , the imaginary part of solution, satisfies the original problem Equations 4.5-4.8, and  $Z(x,t)$  the real part of the solution, satisfies the original problem with the boundary condition Equation 4.7 changed to Equation 4.9. The governing equation for the complex transient seepage becomes

$$\frac{\partial \tilde{H}}{\partial t} = \frac{T}{S} \frac{\partial^2 \tilde{H}}{\partial x^2} \quad (4.11)$$

$$\tilde{H}(x,0) = 0 \quad (4.12)$$

$$\tilde{H}(0,t) = (1+i)h_0 \exp\left(\frac{L}{S}t\right) + h_1 \exp(i\omega t) \exp\left(\frac{L}{S}t\right) \quad (4.13)$$

$$\lim_{x \rightarrow \infty} \tilde{H}(x,t) \rightarrow 0 \quad (4.14)$$

In Equation 4.13, Euler's relationship was used

$$\exp(i\omega t) = \cos(\omega t) + i \sin(\omega t) \quad (4.15)$$

The Laplace transform is applied to Equations 4.11 to 4.14 yielding

$$\frac{d^2 \bar{H}}{dx^2} - \frac{pS}{T} \bar{H} = 0 \quad (4.16)$$

$$\bar{H}(0) = \frac{1+i}{p - \frac{L}{S}} h_0 + \frac{h_1}{p - \frac{L}{S} - i\omega} \quad (4.17)$$

$$\lim_{x \rightarrow \infty} \bar{H}(x) \rightarrow 0 \quad (4.18)$$

where the term  $\bar{H}(x)$  is the Laplace transform of  $\tilde{H}(x,t)$  and  $p$  is the parameter in the transform. The solution to Equation 4.16 subject to Equations 4.17 and 4.18 is

$$\bar{H}(x) = \left( \frac{1+i}{p - \frac{L}{S}} h_0 + \frac{h_1}{p - \left(i\omega + \frac{L}{S}\right)} \right) \exp\left(-x \sqrt{\frac{pS}{T}}\right) \quad (4.19)$$

The inverse Laplace transform from Carslaw and Jaeger (1963) applicable to Equation 4.19 in its original notation is

$$L^{-1}\left\{\frac{e^{-a\sqrt{p}}}{p-\omega}\right\}=\frac{1}{2}e^{\omega t}\left[e^{-a\sqrt{\omega}}\operatorname{erfc}\left(\frac{a}{2\sqrt{t}}-\sqrt{\omega t}\right)+e^{a\sqrt{\omega}}\operatorname{erfc}\left(\frac{a}{2\sqrt{t}}+\sqrt{\omega t}\right)\right] \quad (4.20)$$

When the inverse transform is applied to the Equation 4.19, the result is

$$\begin{aligned} \tilde{H}(x,t)= & \left(\frac{1+i}{2}\right)h_0 \exp\left(\frac{L}{S}t\right) \left[ \begin{aligned} & \exp\left(-x\sqrt{\frac{L}{T}}\right)\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\frac{L}{S}t}\right)+ \\ & \exp\left(x\sqrt{\frac{L}{T}}\right)\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\frac{L}{S}t}\right) \end{aligned} \right] + \\ & \frac{1}{2}h_1 \exp\left(i\omega+\frac{L}{S}t\right) \left[ \begin{aligned} & \exp\left(-x\sqrt{\frac{S}{T}\left(i\omega+\frac{L}{S}\right)}\right)\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)+ \\ & \exp\left(x\sqrt{\frac{S}{T}\left(i\omega+\frac{L}{S}\right)}\right)\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right) \end{aligned} \right] \end{aligned} \quad (4.21)$$

Equation 4.21 should be separated into its real and imaginary parts to be applicable to practical problems. The treatment of the real and imaginary parts of the complex function (Equation 4.21) is the same as the procedure of Fourier as cited by Tikhonov and Samarskii (1963) and detailed in Section 3.2. The same method is followed here. Separation of the expression

$$E(x,t)=\frac{1}{2}h_1 \exp(i\omega t) \exp\left(\frac{L}{S}t\right) \left[ \begin{aligned} & \exp\left(-x\sqrt{\frac{iS\omega}{T}+\frac{L}{T}}\right)\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)+ \\ & \exp\left(x\sqrt{\frac{iS\omega}{T}+\frac{L}{T}}\right)\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right) \end{aligned} \right] \quad (4.22)$$

from Equation 21 into its real and imaginary parts is discussed term by term. By applying Euler's relationship

$$\exp\left(\mp x\sqrt{\frac{iS\omega}{T} + \frac{L}{T}}\right) = \exp\left(\mp \sqrt{\frac{Sr}{T}} \cos \frac{\theta}{2}\right) \left\{ \cos\left(x\sqrt{\frac{Sr}{T}} \sin \frac{\theta}{2}\right) + i \sin\left(\mp \sqrt{\frac{Sr}{T}} \sin \frac{\theta}{2}\right) \right\} \quad (4.23)$$

where  $r = \frac{\sqrt{(S\omega)^2 + L^2}}{T}$  and  $\theta = \arctan\left(\frac{S\omega}{L}\right)$ .

Next, the complementary error function can be expanded as (Abramowitz and Stegun, 1965)

$$\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{\left(i\omega + \frac{L}{S}\right)t}\right) = \operatorname{erfc}(R1 + iI1) \quad (4.24)$$

$$\operatorname{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{\left(i\omega + \frac{L}{S}\right)t}\right) = \operatorname{erfc}(R2 + iI2) \quad (4.25)$$

where

$$R1 = \frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{r_1 t} \cos \frac{\theta}{2} \quad (4.26)$$

$$R2 = \frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{r_1 t} \cos \frac{\theta}{2} \quad (4.27)$$

$$I1 = -\sqrt{r_1 t} \sin \frac{\theta}{2} \quad (4.28)$$

$$I2 = \sqrt{r_1 t} \sin \frac{\theta}{2} \quad (4.29)$$

where  $r_1 = \frac{\sqrt{(S\omega)^2 + L^2}}{S}$  and  $\theta$  are defined as in Equation 4.23.

To evaluate the complementary error function of a complex number, the following approximation is used (Abramowitz and Stegun, 1965):

$$\operatorname{erf}(R + iI) = F(R, I) + iG(R, I) + \varepsilon(R, I) \quad (4.30)$$

where  $\operatorname{erfc}(y) = 1 - \operatorname{erf}(y)$ , and

$$F(R, I) = \operatorname{erf}(R) + \frac{\exp(-R^2)}{2\pi R} (1 - \cos(2RI)) + \frac{2}{\pi} \exp(-R^2) \sum_{n=1}^{\infty} \frac{\exp(-n^2/4)}{n^2 + 4R^2} f_n(R, I) \quad (4.31)$$

$$G(R, I) = \frac{\exp(-R^2)}{2\pi R} \sin(2RI) + \frac{2}{\pi} \exp(-R^2) \sum_{n=1}^{\infty} \frac{\exp(-n^2/4)}{n^2 + 4R^2} g_n(R, I) \quad (4.32)$$

$$f_n(R, I) = 2R - 2R \cosh(nI) \cos(2RI) + n \sinh(nI) \sin(2RI) \quad (4.33)$$

$$g_n(R, I) = 2R \cosh(nI) \sin(2RI) + n \sinh(nI) \cos(2RI) \quad (4.34)$$

and

$$\varepsilon \approx 10^{-16} |\operatorname{erf}(R + iI)| \quad (4.35)$$

As  $\varepsilon \approx 10^{-16} |\operatorname{erf}(R + iI)|$ , and  $\operatorname{erf}(R + iI)$  has a maximum value of 2, negligible error is introduced into the calculations when using Equation 4.30.

Now Equation 4.21 can be separated into the portion applicable to the sine boundary condition, Equation 4.3 and cosine boundary condition, Equation 4.5. The solution to the original problem with sine boundary condition, Equations 4.1 through 4.4:

$$h(x, t) = \operatorname{Im}\{\tilde{H}(x, t)\} \exp\left(-\frac{L}{S}t\right) \quad (4.36)$$

where  $\operatorname{Im}\{\tilde{H}(x, t)\}$  is the imaginary part of  $\tilde{H}(x, t)$  where

$$\begin{aligned}
\text{Im}\{\tilde{H}(x,t)\} = & \frac{1}{2}h_0 \exp\left(\frac{L}{S}t\right) \left[ \exp\left(-x\sqrt{\frac{L}{T}}\right) \text{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{\frac{L}{S}}t\right) \right. \\
& \left. + \exp\left(x\sqrt{\frac{L}{T}}\right) \text{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{\frac{L}{S}}t\right) \right] \\
& + \frac{1}{2}h_1 \cos(\omega t) \exp\left(\frac{L}{S}t\right) \left\{ \exp\left(-x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & -\cos\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R1, I1) \\ & + \sin\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R1, I1)) \end{aligned} \right] + \right. \\
& \left. \exp\left(x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & -\cos\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R2, I2) \\ & + \sin\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R2, I2)) \end{aligned} \right] \right\} \\
& + \frac{1}{2}h_1 \sin(\omega t) \exp\left(\frac{L}{S}t\right) \left\{ \exp\left(-x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & \cos\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R1, I1)) \\ & + \sin\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R1, I1) \end{aligned} \right] + \right. \\
& \left. \exp\left(x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \begin{aligned} & \cos\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R2, I2)) \\ & \sin\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R2, I2) \end{aligned} \right] \right\}
\end{aligned} \tag{4.37}$$

Similarly, the solution to the problem with cosine boundary condition, Equations 4.5, 4.6, 4.8, and 4.9 is

$$Z(x,t) = \text{Re}\{\tilde{H}(x,t)\} \exp\left(-\frac{L}{S}t\right) \tag{4.38}$$

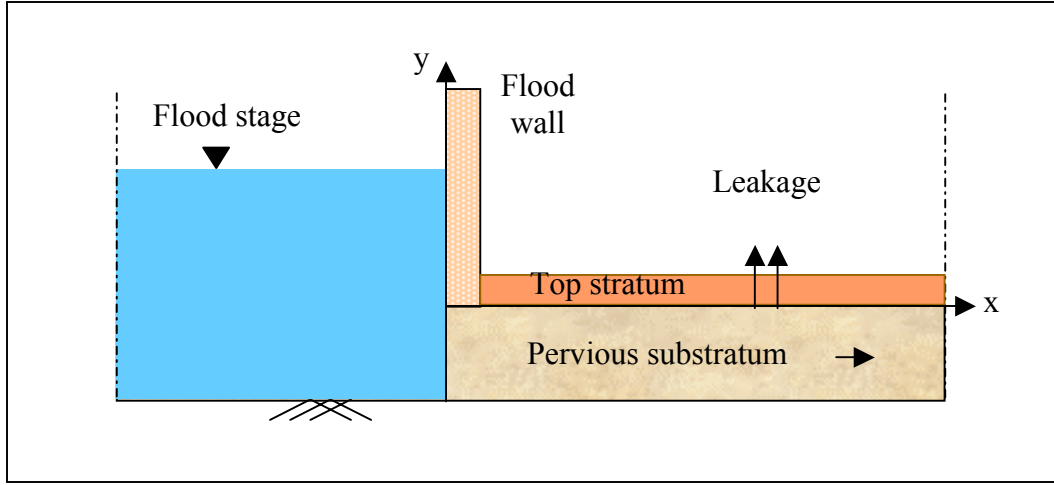
where  $\text{Re}\{\tilde{H}(x,t)\}$  is the real part of  $\tilde{H}(x,t)$ .

$$\begin{aligned}
\text{Re}\{\tilde{H}(x,t)\} = & \frac{1}{2}h_0 \exp\left(\frac{L}{S}t\right) \left[ \exp\left(-x\sqrt{\frac{L}{T}}\right) \text{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{\frac{L}{S}t}\right) \right. \\
& \left. + \exp\left(x\sqrt{\frac{L}{T}}\right) \text{erfc}\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{\frac{L}{S}t}\right) \right] \\
& \frac{1}{2}h_1 \cos(\omega t) \exp\left(\frac{L}{S}t\right) \left\{ \begin{aligned} & \exp\left(-x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R1, I1)) \right. \\ & \left. + \sin\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R1, I1) \right] + \\ & \exp\left(x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R2, I2)) \right. \\ & \left. + \sin\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R2, I2) \right] \end{aligned} \right\} \\
& + \frac{1}{2}h_1 \sin(\omega t) \exp\left(\frac{L}{S}t\right) \left\{ \begin{aligned} & \exp\left(-x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R1, I1) \right. \\ & \left. - \sin\left(-x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R1, I1)) \right] + \\ & \exp\left(x\sqrt{r} \cos\left(\frac{\theta}{2}\right)\right) \left[ \cos\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) G(R2, I2) \right. \\ & \left. - \sin\left(x\sqrt{r} \sin\left(\frac{\theta}{2}\right)\right) (1 - F(R2, I2)) \right] \end{aligned} \right\}
\end{aligned} \tag{4.39}$$

Equation 4.39 is the solution to the problem introduced in Equations 4.1 through 4.4. This solution is applicable to determine time-dependent hydraulic head development beneath the levee when there is leakage out of the aquifer in response to the stage fluctuations observed in the river. Although the solution can be evaluated by mathematical software, it is a long and complex solution. Therefore, an approximate method to solve the same problem was studied and presented in the next section.

### 4.3 Analytical Modeling of Transient Hydraulic Head with Leakage Out of a Confined Aquifer by an Approximate Method

This solution follows the methodology outlined in Section 3.3 and originally presented by Jiao and Tang (1999) for an approximate solution to a problem of groundwater response to tidal fluctuation in a leaky confined aquifer. A schematic view of the model is shown in Fig. 4.2.



**Fig. 4.2 Schematic view of confined flow with leakage out of aquifer for an approximate solution.**

The governing equations for confined flow with initial and boundary conditions are

$$\frac{\partial h}{\partial t} = \frac{T}{S} \frac{\partial^2 h}{\partial x^2} - \frac{L}{S} (h_0 - h) \quad (4.40)$$

$$h(x, 0) = h_0 \quad (4.41)$$

$$h(0, t) = h_0 + h_1 \sin(\omega t) \quad (4.42)$$

$$\lim_{x \rightarrow \infty} h(x, t) = h_0 \quad (4.43)$$

where  $h_0$  is the initial head at  $t = 0$ ,  $L$  is leakage, the ratio of hydraulic conductivity of the semi-confining layer to the thickness of semi-confining layer with units  $\text{time}^{-1}$ . Let



$H = h - h_0$ , then the differential equation with initial and boundary conditions becomes:

$$\frac{\partial H}{\partial t} = \frac{T}{S} \frac{\partial^2 H}{\partial x^2} + \frac{L}{S} H \quad (4.44)$$

$$H(x, 0) = 0 \quad (4.45)$$

$$H(0, t) = h_1 \sin(\omega t) \quad (4.46)$$

$$\lim_{x \rightarrow \infty} H(x, t) = 0 \quad (4.47)$$

Equation 4.40 is in the form of  $H(0, t) = h_1 \text{Im} e^{i(\omega t)}$ , the solution can be assumed as

$$H(x, t) = h_1 e^{\lambda x} e^{i(\omega t)} \quad (4.48)$$

The assumed solution (Equation 4.48) is substituted in Equation 4.44, and  $\lambda^2$  is derived

$$\lambda^2 = \frac{i\omega S}{T} - \frac{L}{T} \quad (4.49)$$

where  $\lambda$  must be a complex number. Let  $\lambda = -p + iq$ , then the real and imaginary parts of Equation 4.49 are equated and  $p$  and  $q$  are derived as

$$p = \frac{1}{\sqrt{2}} \left\{ \left[ \left( \frac{L}{T} \right)^2 + \left( \frac{\omega S}{T} \right)^2 \right]^{1/2} - \frac{L}{T} \right\} \quad (4.50)$$

$$q = -\frac{\omega S}{2pT} \quad (4.51)$$

Substituting  $\lambda$  in Equation 4.48, and using the fluctuating boundary condition, Equation 4.46

$$H(x, t) = h_1 \text{Im}[e^{-px} e^{i(\omega t + qx)}] \quad (4.52)$$

$$H(x, t) = h_1 e^{-px} \sin(\omega t + qx) \quad (4.53)$$

Back to the original problem, the solution of Equation 4.40 subject to boundary conditions Equation 4.42, 4.43 is

$$h(x,t) = h_0 + h_1 e^{-px} \sin\left(\omega t - \frac{\omega S}{2pT} x\right) \quad (4.54)$$

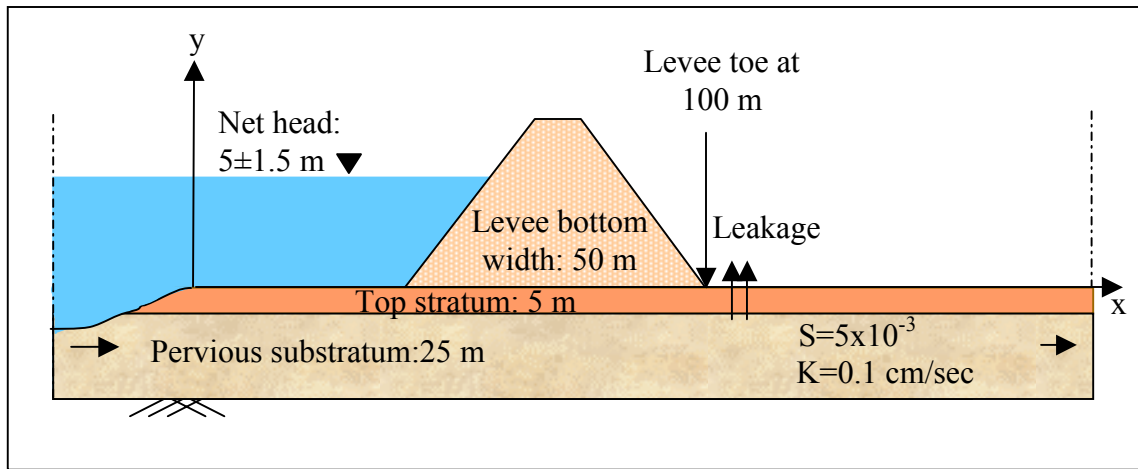
where  $p$  is as defined in Equation 4.50.

Therefore, an approximate solution was found to the problem defined in Equations 4.40 through 4.43. This is an approximate solution because the final solution was initially assumed as shown in Equation 4.48. In addition, the final solution, Equation 4.54, does not satisfy the initial condition specified in Equation 4.41. Thus, the final solution is referred to as a quasi steady-state solution.

#### 4.4 Results and Discussion

A typical levee section defined by the Army Corps is selected for analysis purposes (EM 1110-2-1913). The thickness of sandy alluvium under Mississippi River levees varies from 25 m to 45 m. The thickness of low permeable blanket layer under Mississippi River levees varies from 1.5 m to 37.5 m. The hydraulic conductivity of sandy alluvium ranges from 0.1 cm/sec to 0.2 cm/sec (Turnbull and Mansur 1961). Typical storativity values for confined aquifers are  $5 \times 10^{-3}$ ,  $5 \times 10^{-4}$  and  $5 \times 10^{-5}$  (Freeze and Cherry, 1979). In the 1993 floods, the net river level elevation change of the middle Mississippi River levees was recorded as 4.8 to 6.7 m (Mansur *et al.* 2000). A net head of 5 m and a fluctuation of 1.5 m were selected in the analysis. The typical levee section with selected aquifer parameters and hydraulic head is shown in Fig. 4.3.

The flood duration was selected as 60 days. The net head starts at 5 m, rises to the peak of 6.5 m at time=30 days, and falls back to 5 m at time=60 days. Head development over a distance of 200 m was determined, which included 50 m at riverside, a 50 m levee base, and 100 m on the landside of the levee.



**Fig. 4.3 Typical levee section with selected parameters (not in scale).**

The analysis was restricted to 100-m landside of the levee because, as noted in the literature review, Li *et al.* (1996) reported that there was no significant evidence of surface seepage beyond 100 m from the levee north of Cairo, Illinois after the 1993 high water. Head development and exit gradients were calculated at the landside of the levee. Calculations were performed by MathCad 2000 software. The leakage amount was selected as 0.14 l/day/m, which corresponds to a 5 gal/min/100 feet of levee, reported by Turnbull and Mansur (1961) and presented in Table 2.1. Figure 4.4 shows the visual explanation for the estimation of leakage out of a confined aquifer. The upward leakage was estimated by Turnbull and Mansur (1961) using the general seepage formula:

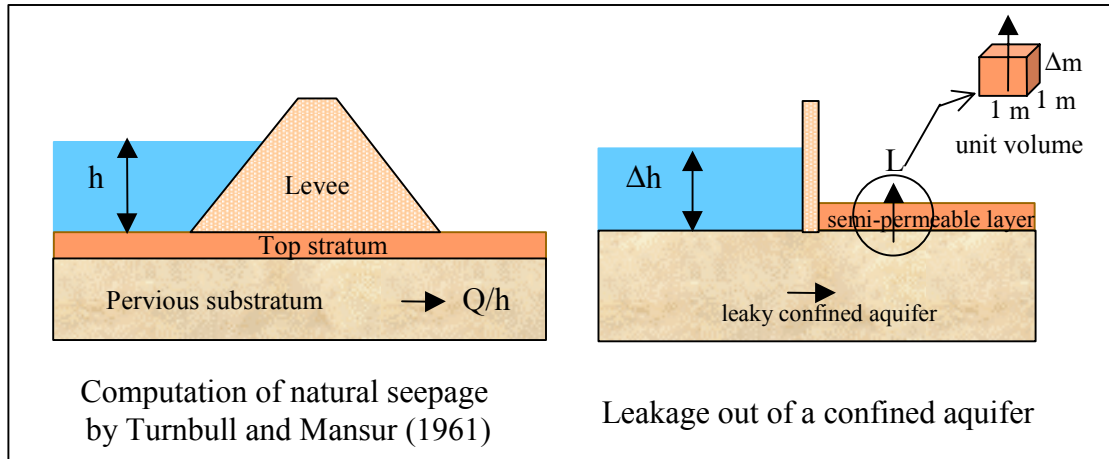
$$Q = kiA \quad (4.55)$$

This horizontal seepage changes its direction and leaks out of the aquifer through semi-pervious top layer as in Figure 4.4. Then, hydraulic gradient under semi-permeable layer,  $i$  is estimated as  $\Delta h / \Delta m$ , where  $\Delta h$  is the hydraulic head difference between the river and landside of levee, and  $\Delta m$  is the thickness of top stratum. Recall that leakage is the ratio of vertical hydraulic conductivity of the semi-confining layer to the thickness of semi-

confining layer,  $L = k/\Delta m$ . Here, a specific seepage is also defined as  $Q_s = Q/h$  which corresponds to the computed natural seepage values,  $Q/h$ , which were reported by Turnbull and Mansur (1961). Therefore, seepage beneath the levee in terms of leakage is:

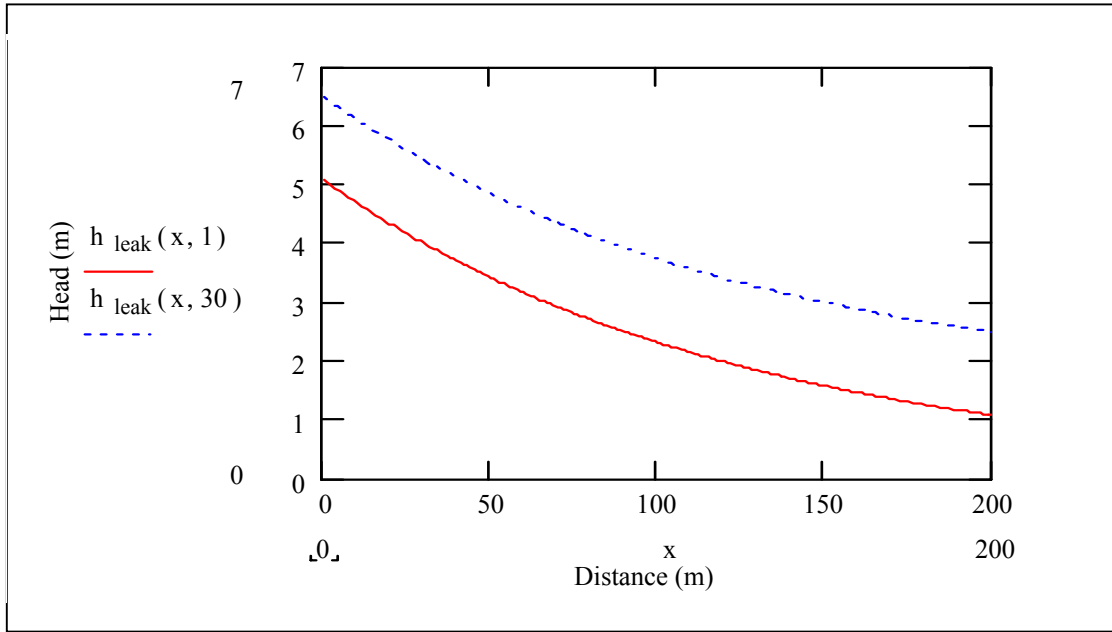
$$Q_s = L\Delta hA \quad (4.56)$$

where  $A$  is the unit area through which seepage passes. Using the maximum hydraulic head difference,  $\Delta h = 6.5$  m, unit area,  $A = 1 \text{ m}^2$ , and seepage amount,  $Q_s = 0.9 \text{ m}^3/\text{d}/\text{m}$ , which corresponds to 5 gal/min/100 ft of levee, then leakage is estimated as,  $L = 0.14 \text{ 1/d}/\text{m}$  of levee.

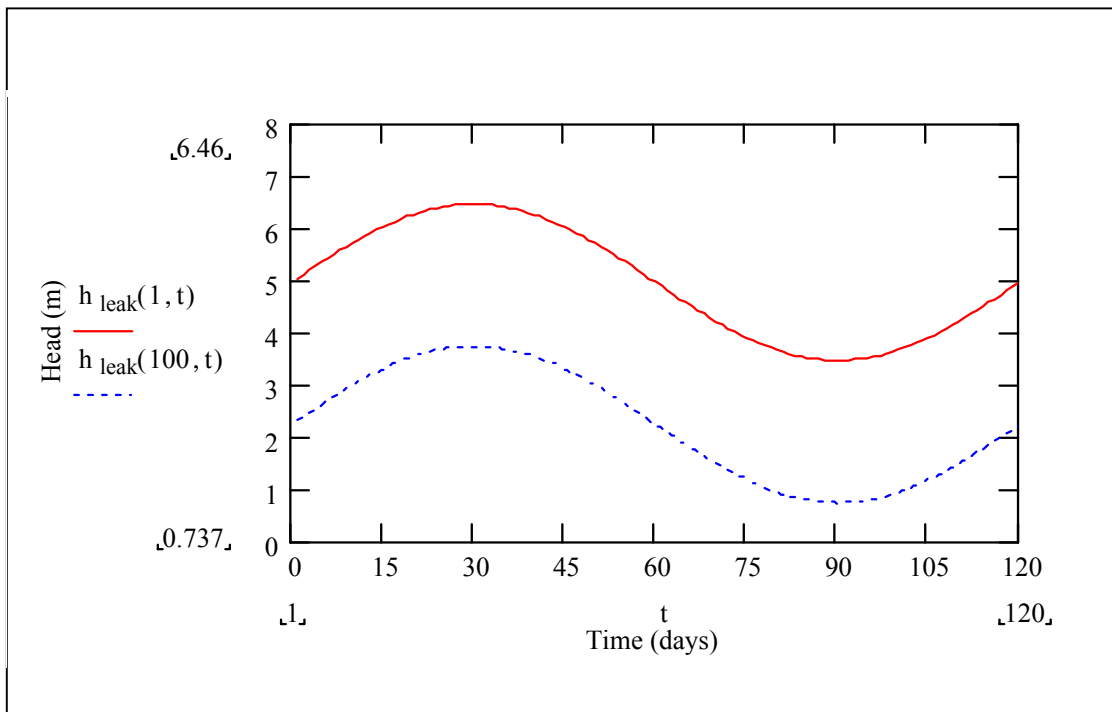


**Fig. 4.4 Detailed figures related to the computation of upward leakage.**

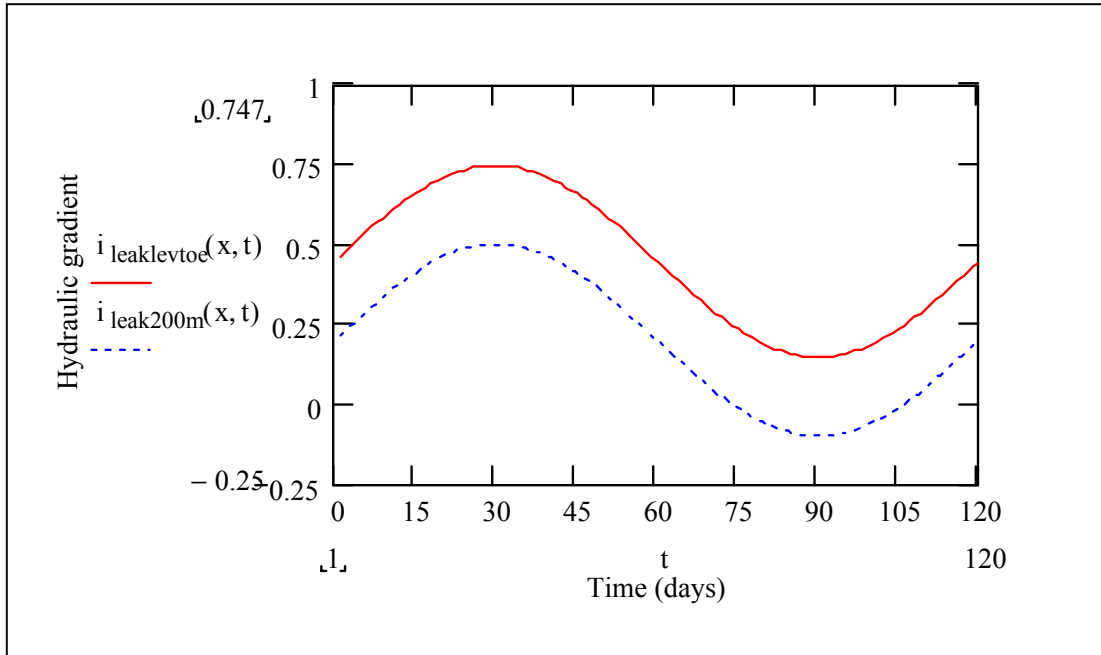
Figures 4.5, 4.6, 4.7, and 4.8 show head development and exit hydraulic gradient distributions by the Laplace transform method when there is a leakage of 0.14 1/day/m of levee. Similarly, Figures 4.9, 4.10, 4.11, and 4.12 show the results by the approximate method.



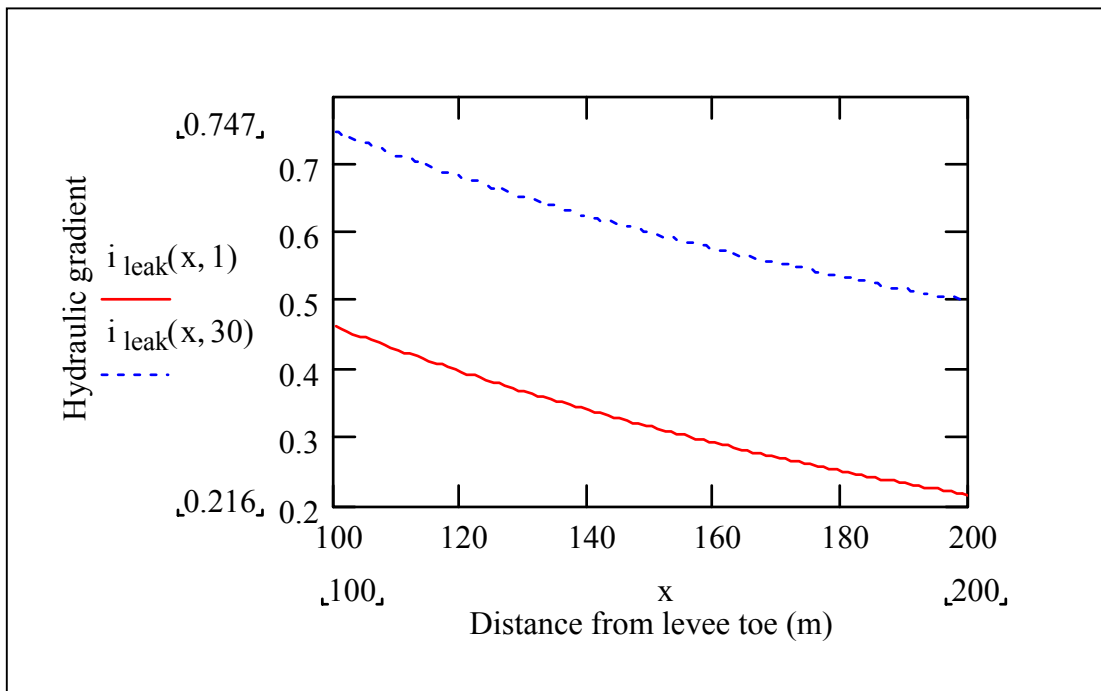
**Fig. 4.5 Transient head development at  $t=1$  day and 30 days by Laplace transform method with leakage,  $L=0.14$  1/day/m of levee.**



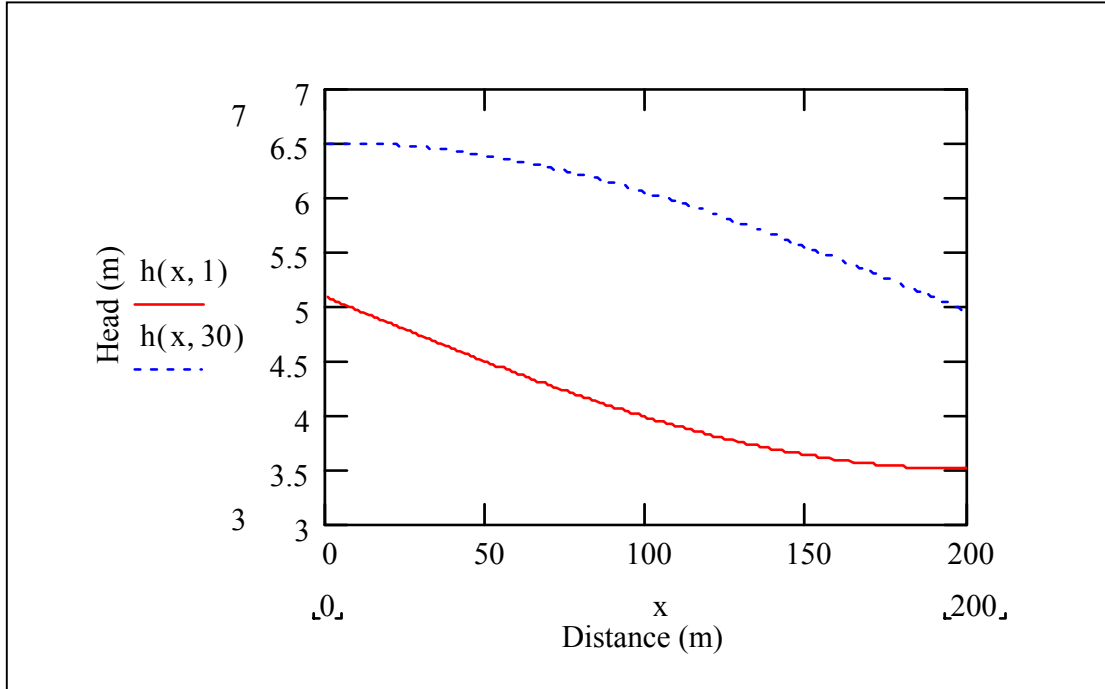
**Fig. 4.6 Transient head development at  $x=1$  m and  $x=100$  m, levee toe, by Laplace transform method with leakage,  $L=0.14$  1/day/m of levee.**



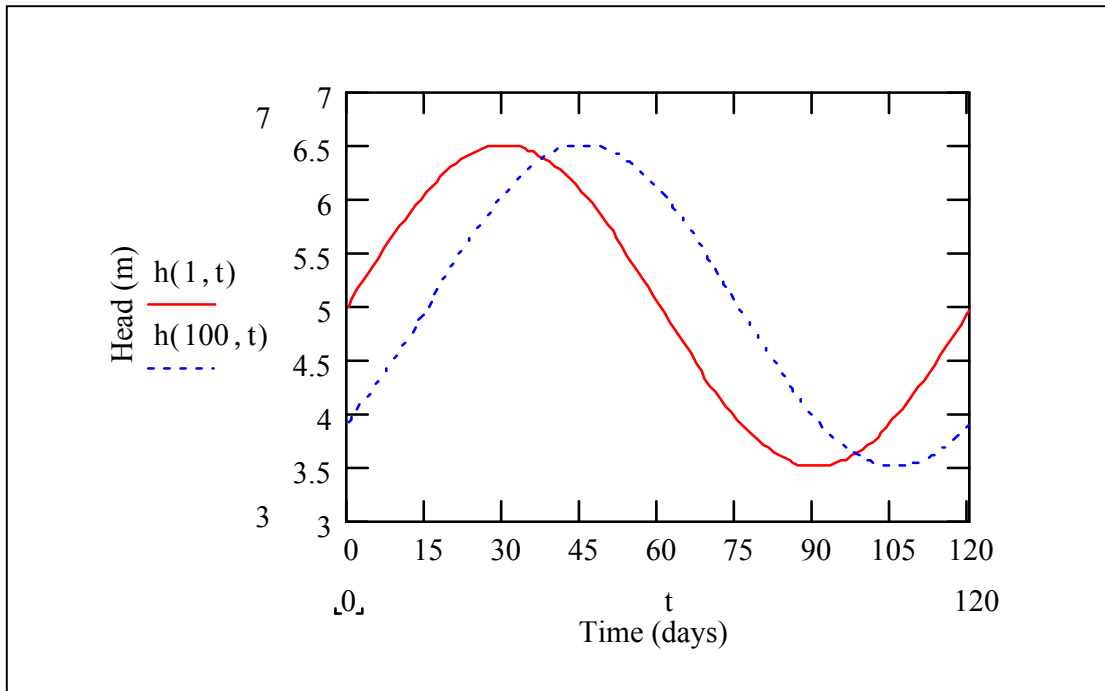
**Fig. 4.7 Transient exit gradient at the levee toe and at 200 m landward of levee by Laplace transform method with leakage,  $L=0.14$  1/day/m of levee.**



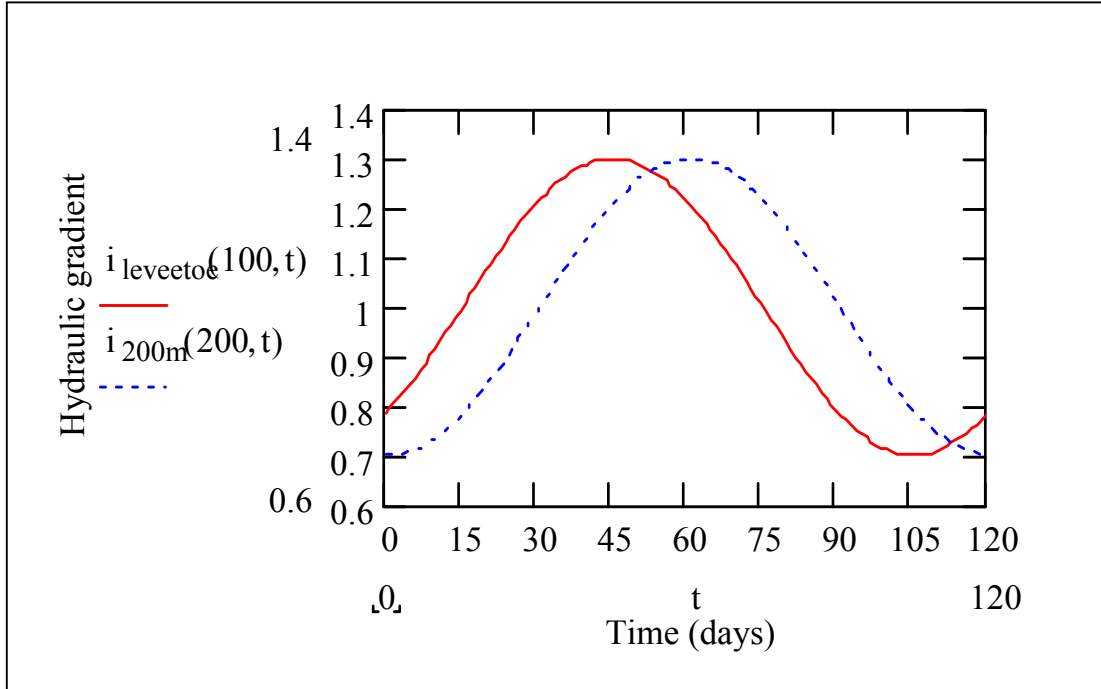
**Fig. 4.8 Transient exit gradient at  $t=1$  day and  $t=30$  days at landside of the levee by Laplace transform method with leakage,  $L=0.14$  1/day/m of levee.**



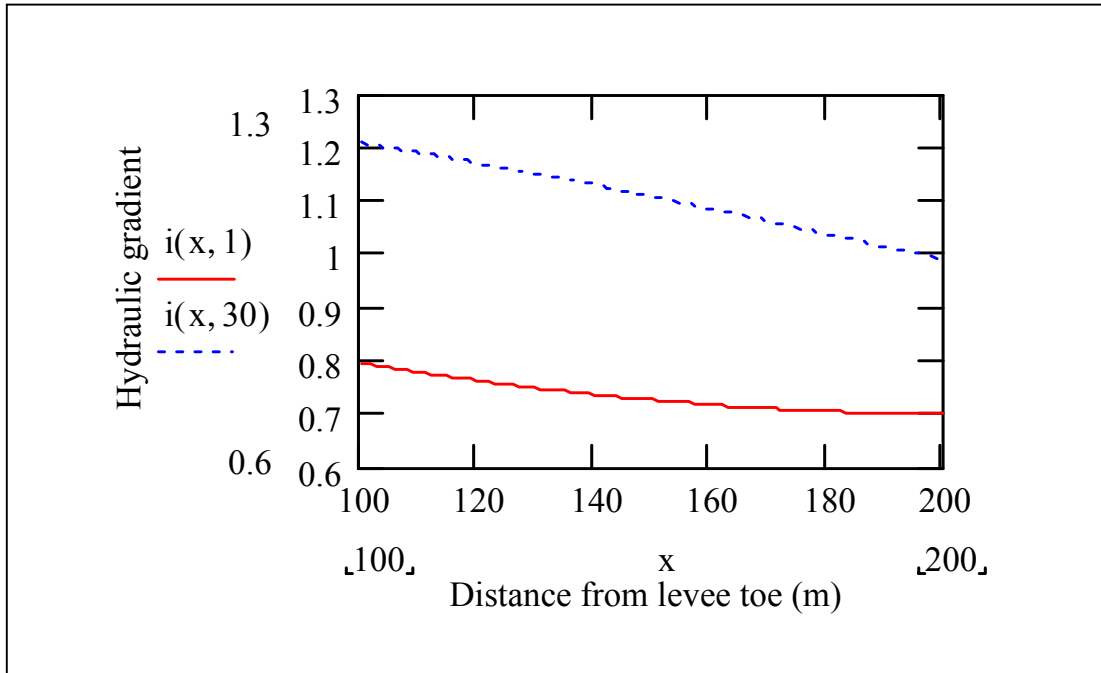
**Fig. 4.9 Transient head development at  $t=1$  day and 30 days by the approximate method with leakage,  $L=0.14$  1/day/m of levee.**



**Fig. 4.10 Transient head development at  $x=1$  m and  $x=100$  m, levee toe, by the approximate method with leakage,  $L=0.14$  1/day/m of levee.**



**Fig. 4.11** Transient exit gradient at the levee toe and at 200 m landside of the levee by the approximate method with leakage,  $L=0.14$  1/day/m of levee.



**Fig. 4.12** Transient exit gradient at  $t=1$  day and  $t=30$  days at landside of the levee by the approximate method with leakage,  $L=0.14$  1/day/m of levee.

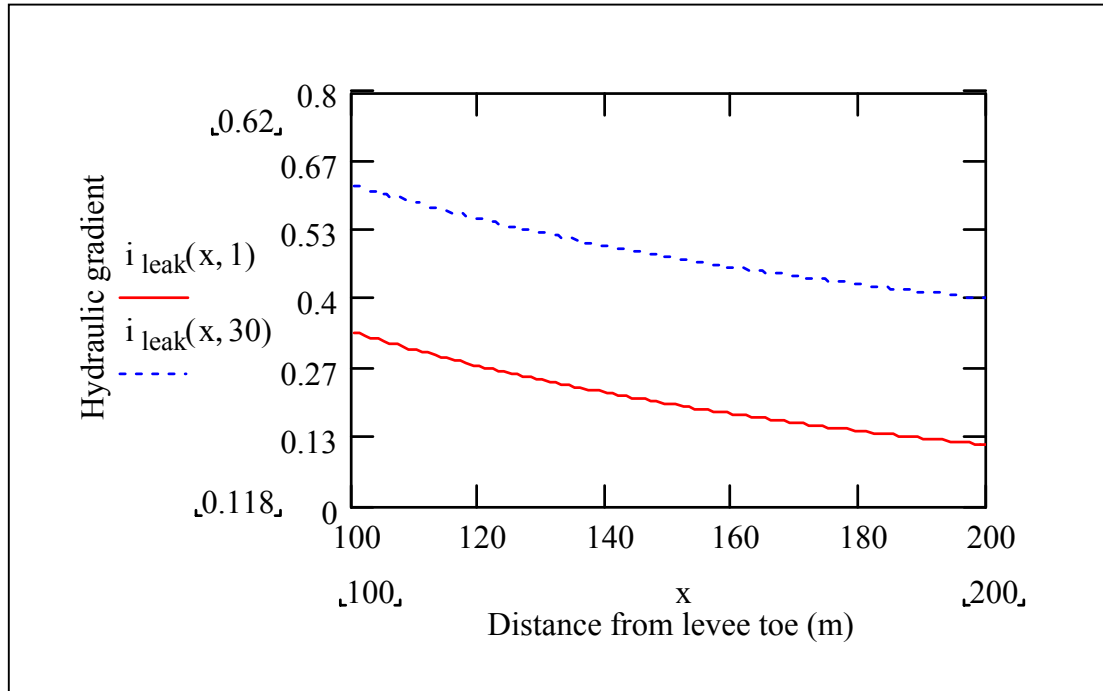


In general, the Laplace transform solution gives higher decreases in head and hydraulic gradient with distance from the landside of the levee than does the approximate method does. The results are summarized in Table 4.1.

**Table 4.1 Head and hydraulic gradient development by Laplace transform and approximate solution with a leakage of 0.14 1/day/m of levee.**

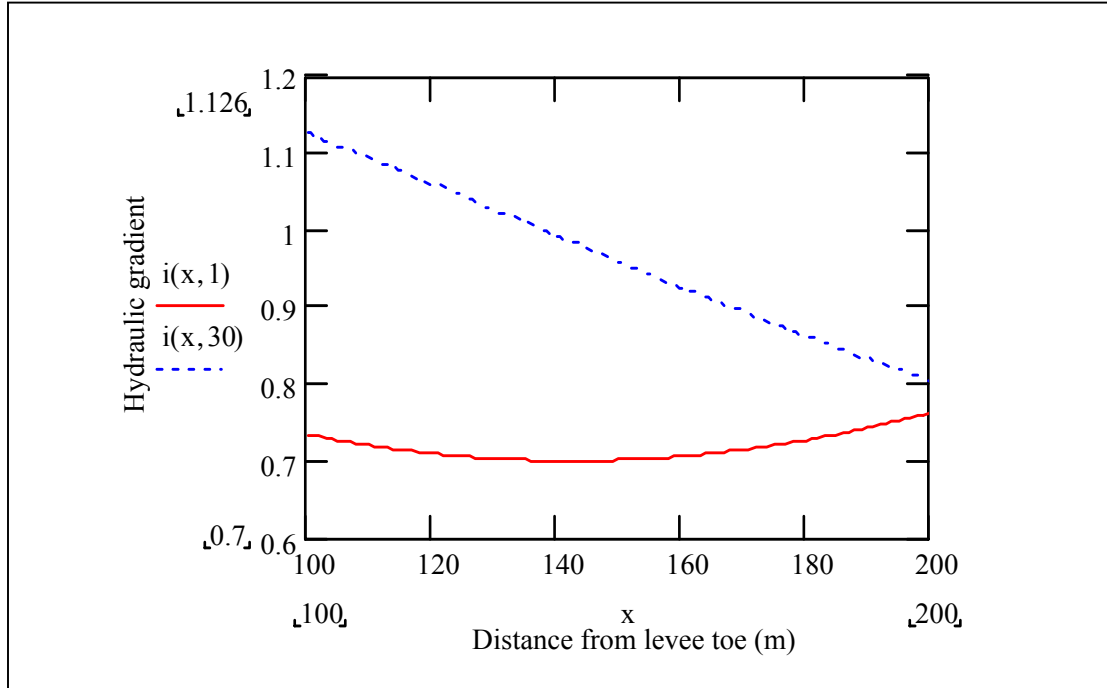
	Time (days)	Laplace Transform Method	Approximate Method
Head at levee toe (m)	1	2.31	3.98
	30	3.73	6.04
Head at 100 m farther than levee toe (m)	1	1.08	3.50
	30	2.50	4.94
Hydraulic gradient at levee toe	1	0.46	0.80
	30	0.75	1.21
Hydraulic gradient at 100 m farther than levee toe	1	0.22	0.70
	30	0.50	0.99

Turnbull and Mansur (1962) reported that the exit gradient was in the range of 0.2 to 0.5 when there was 5 gal/min/100 feet of levee of seepage (Table 2.1). The Laplace transform solution results in an exit gradient of 0.75 at the levee toe and 0.22 at 100 m farther from the levee toe. As mentioned before, sand boils are most likely to occur within this distance. The approximate method results in an exit gradient in the range of 0.70 to 1.21, over the same distance, which is higher than the observed values in the field studies. Similarly, when there was 10 gal/min/100 feet of levee of seepage the exit gradient was reported to be in the range of 0.4 to 0.6 (Turnbull and Mansur, 1962). A seepage amount of 10 gal/min/100 feet of levee corresponds to a leakage of  $L = 0.28$  1/day/m of levee (Equation 55). Figure 4.13 shows the exit gradient distribution by Laplace transform method for this case.



**Fig. 4.13 Transient exit gradient at  $t=1$  day and  $t=30$  days at landside of the levee by Laplace transform method with leakage,  $L=0.28$  1/day/m of levee.**

As shown in Fig. 4.13, the exit gradient is in the range of 0.12 to 0.62 during the rising limb of flood wave from the levee toe to 100 m further than levee toe. The same condition is also analyzed by the approximate method. Figure 4.14 shows hydraulic gradient distribution by the approximate method when there is a leakage of 0.28 1/day/m of levee. Figure 4.14 shows that the exit gradient is in the range of 0.70 to 1.13 by the approximate method when there is a leakage corresponding to 10 gal/min/100 feet of levee. Table 4.2 summarizes this discussion. As shown in Table 4.2, the results of the transient analytical model with Laplace transform method coincide with the results of the limited number of field studies. However, the approximate method does not yield any close results to the field studies. In addition, the approximate solution shows very little dampening by time and distance as shown in Table 4.1 in response to upward leakage from the aquifer.



**Fig. 4.14 Transient exit gradient at  $t=1$  day and  $t=30$  days at landside of the levee by the approximate method with leakage,  $L=0.28$  1/day/m of levee.**

**Table 4.2 Exit gradient at landside of levee by Laplace transform method, approximate method and field observed values for Q=5 gal/min and 10 gal/min for 100 feet of levee.**

Seepage Quantity (Leakage)	Location	Time (days)	Laplace Transform Method	Approximate method	Reported by Turnbull and Mansur (1961)
5 gal/min/100 feet of levee, (L=0.14 1/day/m of levee)	Levee toe	1	0.46	0.80	0.2-0.6
	100 m from levee toe	1	0.22	0.70	
	Levee toe	30	0.75	1.21	
	100 m from levee toe	30	0.50	0.99	
10 gal/min/100 feet of levee, (L=0.28 1/day/m of levee)	Levee toe	1	0.34	0.74	0.4-0.7
	100 m from levee toe	1	0.12	0.76	
	Levee toe	30	0.62	1.13	
	100 m from levee toe	30	0.40	0.85	

Both methods can be further investigated by using a more extensive summary of 1950 high water data at piezometer sites in the Lower Mississippi River Valley presented by Turnbull and Mansur (1961). The researchers concluded that the hydrostatic pressure ratio at the landside toe of the levee ( $h_0/H$ ) varied from 20% to 75% depending on site and soil conditions. The same parameters were applied to the transient flow models and the results were presented in Table 4.3. The hydrostatic pressure ratio at the landside toe of the levee ( $h_0/H$ ) varied from 21% to 75% by the Laplace transform method, and 3% to 99% by the approximate method (Table 4.3).

**Table 4.3 Comparison of hydraulic head by Laplace transform method, approximate method and field observations of 1950 high water.**

Site	H (ft)*	x (ft)*	Seepage (Q/H) (gpm/100 ft of levee)	$h_0/H$ (%) (1950)	$h_0/H$ (%) Laplace Trans. Method	$h_0/H$ (%) Approx. Method
Caruthersville, MO	9.4	4,530	28	21	34	91
Gammon, AR	11.9	20,500	11.3	28	22	99
Commerce, MS	9.2	2,200	9.9	25	35	98
Trotters 51, MS	9.0	3,550	8.1	33	35	40
Trotters 54, MS	13.8	2,975	9.1	22	23	83
Stoval, MS	14.9	3,600	10	44	21	91
Farrell, MS	6.8	5,500	5.5	28	46	82
Upper Francis, MS	8.3	7,250	8.8	21	37	47
Lower Francis, MS	13.6	1,675	25.2	13	23	96
Bolivar, MS	6.5	1,830	15.6	37	49	3
Eutaw, MS	6.2	2,950	4.3	65	52	81
L'Argent, LA	16.4	2,880	1.1	35	20	98
Hole in the Wall, LA	10.4	2,600	3.5	13	31	57
Kelson, LA	16.7	1,180	0.015	28	75	96
Baton Rouge, LA	17.4	710	1.1	73	33	74

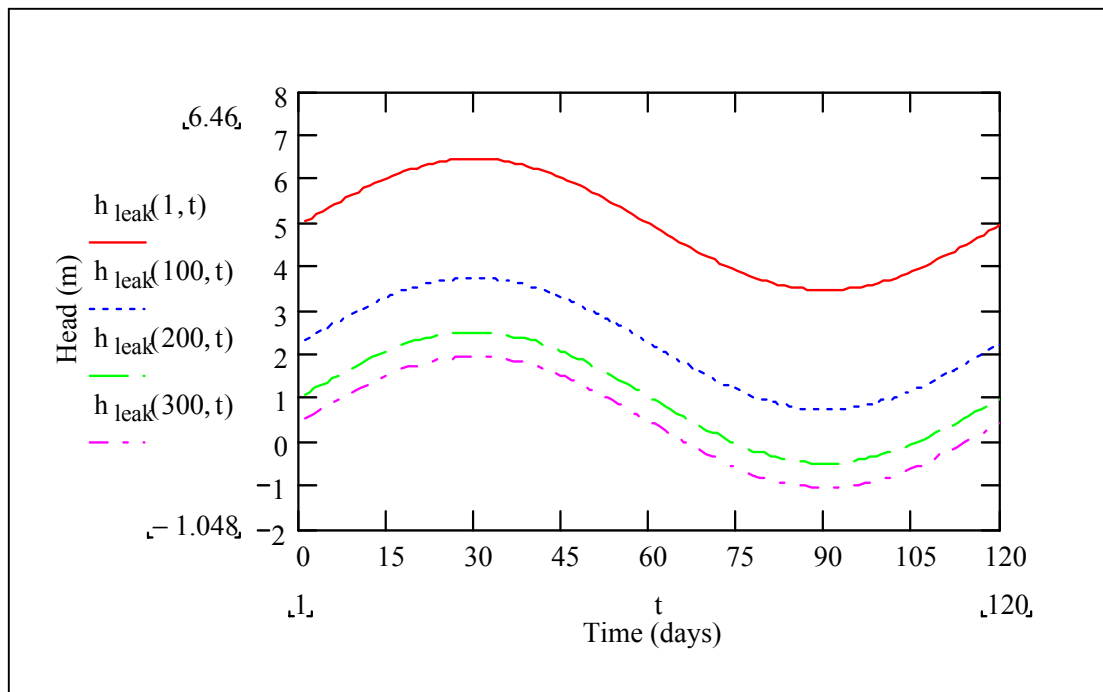
\* H: height of flood stage, x: distance from landside toe of the levee to effective source of seepage entry.

In Table 4.3 seepage values were computed by using Bennett's (1946) analytical solutions as presented in The Army Engineer Manual (EM) 1110-2-1913 (Turnbull and Mansur, 1961). They also stated that about 64% of seepage flow rises to the surface between the landside levee toe and the effective seepage exit according to the blanket formulas. Therefore in the analysis, the leakage value was estimated as 64% of the computed seepage value for each site. According to the results presented in Tables 4.2

and 4.3, the Laplace Transform method performs well compared with the field observations.

#### Time Lag in Head Development

In the field, one would expect to observe a time difference in head development between the river, at the levee toe, and with distance on the landside of the levee. The Laplace Transform solution does not yield any significant time differences in head development at various distances (Fig. 4.15). This figure shows considerable dampening in head development by time due to leakage, however, little time lag occurs between the head curves at various distances.



**Fig. 4.15 Transient head development beneath the levee at various distances from the river by Laplace transform method.**

As noted in Chapter 2 and Chapter 3, Ferris (1951) presented analytical expressions to determine aquifer diffusivity ( $T/S$ ) based on the observed values of amplitude, lag, velocity, and wavelength of the sinusoidal changes in groundwater level.

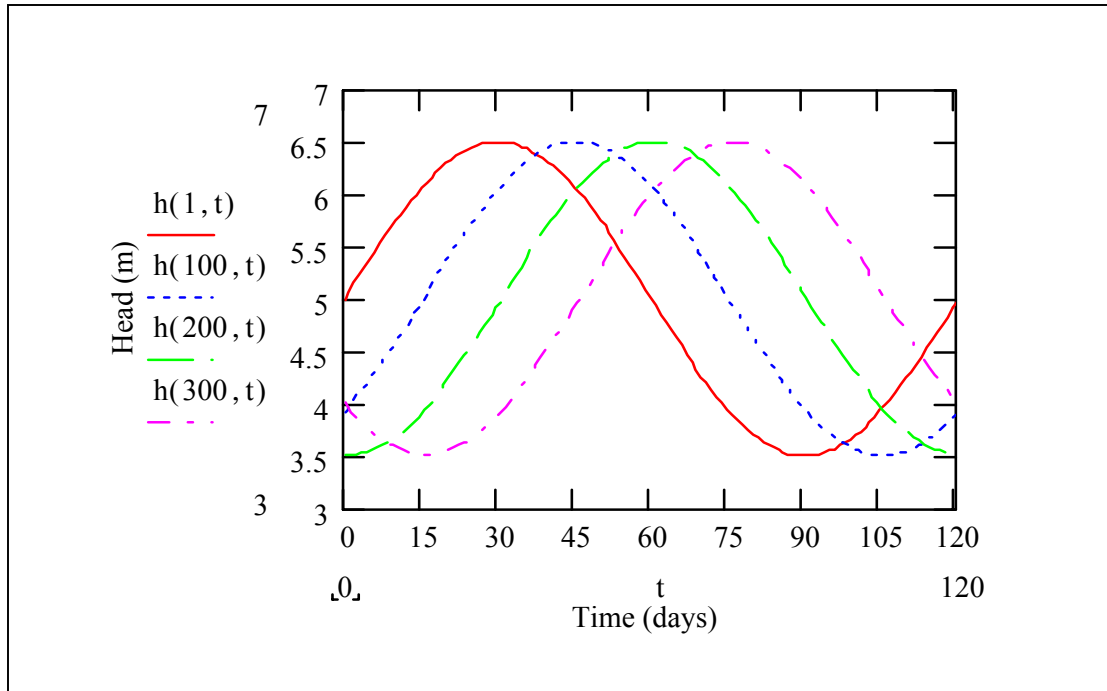
If the time lag between river and groundwater maximum and minimum stages is known then aquifer diffusivity can be estimated by using the following formula (Engineer Manual, EM 1110-2-1421, Equation 6-9)

$$t_{lag} = d \sqrt{\frac{PS}{4\pi T}} \quad (4.56)$$

where  $t_{lag}$  is the lag time in the occurrence of the maximum groundwater stage following the occurrence of a similar surface stage,  $d$  is the distance from an observation well to the river, and  $P$  is the period of uniform tide or stage fluctuations. Equation 4.56 can be applied to time lag analysis of transient head development due to river fluctuations. If the same parameters as in the time lag analysis ( $d = 100$  m,  $P = 60$  days,  $S = 0.005$ ,  $T = 2160$  m<sup>2</sup>/day) of the Laplace transform solution and the approximate method were applied to Equation 4.56, the time lag would result in 0.33 days for every 100-m of distance. This expression does not consider any leakage out of an aquifer. However, one would expect smaller time lags than 0.33 days between the head waves when leakage out of an aquifer occurs.

In addition, as noted in the literature review, according to the observations of a levee collapse near Marysville, California, there was one-day difference between the peak of the flood stage in Feather River and the collapse of the levee. Sand boils were also observed before the collapse of the levee. Part of the time delay may have been due to the time required for sand boils to erode channels or pipes under the levee, undermine it, and accelerate its failure. Also, at Louisiana State University, Dairy Farm, head and seepage rate in one existing sand boil responded very quickly to the river stage fluctuations. Therefore, the lack of time lag shown by the Laplace transform solution in Fig. 4.15 may not be unreasonable.

On the other hand, the approximate solution shows a significant time lag between head fluctuations. Figure 4.16 shows about a 15-day time difference between the peak points of head fluctuations for every 100-m distance from the river. A prediction of time lag between head waves determined from Equation 4.56 and limited field observations suggests that a 15-day time lag between the river and 100 m beyond the levee toe is not reasonable.



**Fig. 4.16 Transient head development beneath the levee at various distances from the river by the approximate method.**

The approximate solution was not nearly as accurate as the Laplace Transform solution and the field studies for estimating hydraulic head developments in a confined aquifer with an upward leakage. Therefore, the approximate solution was eliminated from further analysis of transient flow problems in this research.



## 4.5 Summary

Two transient flow models were developed to describe the hydraulic head development at the landside of a flood wall in response to head fluctuations in the river when there is leakage out of a confined aquifer. This situation simulates surface seepage and sand boil formation. The rising river stage was defined by a sinusoidally varying boundary condition. Both models consider one-dimensional saturated flow conditions in a homogenous isotropic confined aquifer. The first transient flow model was developed by solving the governing diffusion equation and the boundary conditions (Equation 4.1 through 4.4) with the Laplace transform method. This solution method is complicated and can only be evaluated by a mathematical software. Therefore, an approximate solution was also presented. The results were evaluated for a typical levee section.

The Laplace transform solution resulted in considerable head dissipation with time and distance in response to the upward seepage out of the aquifer. The hydraulic gradient by the Laplace transform method was evaluated for different leakage quantities as reported by Turnbull and Mansur (1962). The results were in agreement compared with the field studies. However, the Laplace transform solution did not show any significant time lag between the peak points of head waves at various distances. In other words, the effect of head fluctuations in the river was felt quickly at various distances from the landside of the levee when surface seepage was expected. According to very limited field observations, this was a reasonable result.

The approximate solution did not perform well compared with the limited field studies and the Laplace transform method. The solution showed little dampening in hydraulic head in response to the leakage out of the aquifer. It also showed an unreasonable time lag between head waves at various distances.

The main objective of this chapter was to develop transient flow models for leakage out of a confined aquifer by the Laplace transform method and by an approximate method. This objective was satisfied. The results of the analysis lead us to eliminate the approximate method from further analysis. The applicability and performance analysis of the transient flow model with Laplace transform method will be studied in the following chapters.

#### **4.6 List of Symbols**

$a$  = constant in inverse Laplace Transform

$A$  = unit area ( $L^2$ )

$d$  = distance (L)

$E(x, t)$  = an expression for a part of hydraulic head function

$f_n$  = function used to calculate error function

$F$  = real function used to calculate an error function

$g_n$  = function used to calculate error function

$\varepsilon$  = error of approximation

$G$  = imaginary function used to calculate an error function

$h$  = hydraulic head (L)

$h(x, t)$  = hydraulic head function

$\Delta h$  = hydraulic head difference (L)

$h_0$  = initial hydraulic head (L)

$h_0$  = head beneath top stratum at landside toe of levee (L)

$H$  = height of flood stage (L)

$H_0$  = initial hydraulic head (L)

$h_1$  = amplitude of the variation from the initial hydraulic head (L)

$H_1$  = amplitude of the variation from the initial hydraulic head (L)

$\tilde{H}(x,t)$  = a complex variable to define transformed hydraulic head function

$\overline{H}(x,t)$  = Laplace transform of  $\tilde{H}(x,t)$

$i$  = imaginary unit where  $i^2 = -1$

$L$  = leakage ( $T^{-1}$ )

$I1, I2$  = imaginary part of a complex variable

$n$  = index of summation

$\lambda$  = a complex variable

$p$  = real part of the complex variable  $\lambda$

$p$  = complex number in Laplace transform

$P$  = period of uniform stage fluctuations (T)

$r$  = inverse of length squared ( $L^{-2}$ )

$r_1$  = frequency of a wave ( $T^{-1}$ )

$q$  = imaginary part of the complex variable  $\lambda$

$Q$  = seepage ( $L^3T^{-1}$ )

$R1, R2$  = real part of a complex variable

$S$  = aquifer storativity (dimensionless)

$t$  = time (T)

$t_{lag}$  = time lag (T)

$T$  = aquifer transmissivity ( $LT^{-2}$ )

$x$  = horizontal coordinate (L)

$x$  = distance from landside toe of the levee to effective source of seepage entry (L)

$y$  = variable in error function

$Y(x, t)$  = transformed hydraulic head function (imaginary part of  $\tilde{H}(x, t)$ )

$z_t$  = thickness of landside top stratum

$Z(x, t)$  = transformed hydraulic head function (real part of  $\tilde{H}(x, t)$ )

$\theta$  = phase angle for frequency ratio

$\omega$  = frequency of the flood wave

## CHAPTER 5 CONSTRUCTION OF TRANSIENT FLOW NETS

### 5.1 Introduction

The flow of water through soil is represented by flow nets. A flow net is formed by the network of flow lines and equipotential lines that illustrates graphically how the head or energy varies as water flows through a pervious medium. Flow lines characterize the average flow path of a particle of water from the upstream water to the downstream. The energy of flow is described by lines of equal potential called equipotential lines. A simple method to obtain a flow net is sketching. Other methods besides sketching include mathematical solutions, electrical analogs, viscous-flow models, small-scale laboratory flow models, the method of fragments, and numerical methods (Holtz and Kovacs, 1981).

The objective of this chapter was to construct time-dependent flow nets. The geometry of flow nets is not expected to change with time. Only the numerical values assigned to equipotential and flow lines change with time. The main reason to include such an analysis is because the literature provides little guidance on transient flow nets. To develop equations to construct time dependent flow nets could be an interesting contribution to the literature.

An analytical solution expressed as a flow net is actually a graphical solution of Laplace's equation in two dimensions:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \quad (5.1)$$

In this analysis, time-dependent streamline and equipotential line equations were derived analytically by using complex variables. While complex variables have long been associated with two-dimensional steady flow, there are conditions in which time

dependent boundary conditions can be introduced. The time dependent boundary condition on the riverside of the levee is

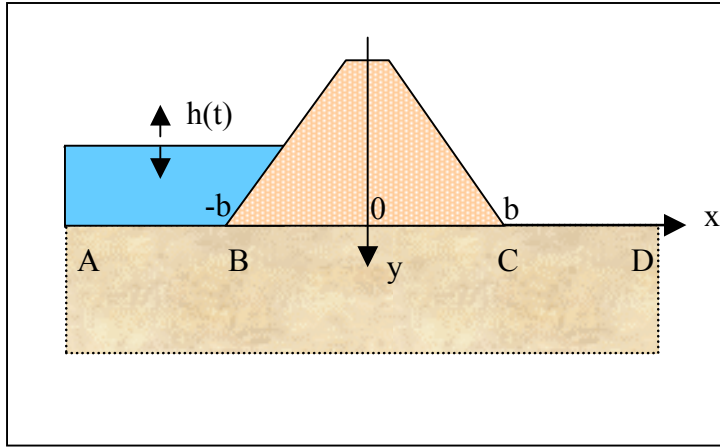
$$h(0, y, t) = h_0 + h_1 \sin(\omega t) \quad (5.2)$$

Here, two solutions of transient flow nets were presented; one for infinite-depth aquifers, and one for finite-depth aquifers. Mathematical analyses presented by Polubarinova-Kochina (1962) were followed. For transient flow nets in an infinite-depth aquifer case, Polubarinova-Kochina (1962) presented a problem with wave actions at both headwater and tail water of a hydraulic structure on a soil of infinite depth. Her examples were for standing waves such as a hydraulic jump that was a function of distance, but not time. Here, her analysis was modified for a time-dependent boundary condition representing a flood-wave. This solution allows us to draw a time-dependent flow net in an infinite-depth semi-confined aquifer. Polubarinova-Kochina (1962) also presented an analytical solution for flow net construction under a hydraulic structure on a layer of finite-depth confined aquifer. Again, her examples were for standing waves as a hydraulic jump that was a function of distance, but not time. The same methodology was followed and a time-dependent head term was introduced into her solution.

## **5.2 Construction of Transient Flow Nets for Infinite Depth Aquifers**

Seepage flow in an infinite depth aquifer under a levee due to fluctuating river head is considered in this section (Fig. 5.1).

The complex potential is defined as  $\omega(z) = \phi + i\psi$ , which is a function of the complex variable,  $z = x + iy$ . A constant value of  $\phi$  represents a line of constant head while a constant value of  $\psi$  represents a particular streamline.



**Fig. 5.1 Flow region in a soil of infinite-depth aquifer.**

Polubarinova-Kochina (1962) introduced the complex function representing the conditions of the complex potential in the flow region

$$f(z) = \frac{\omega(z,t)}{\sqrt{z^2 - b^2}} \quad (5.3)$$

Polubarinova-Kochina (1962) explained the development of a velocity function representing the flow in a soil of infinite depth. A similar analogy is used in the development of the complex potential function, Equation 5.3. As is known

$$\sqrt{z^2 - b^2} = (z - b)^{1/2} (z + b)^{1/2} \quad (5.4)$$

The function (Equation 5.4) is real for  $z < -b$  and  $z > b$ , and imaginary for  $-b < z < b$ .

This expression satisfies the conditions in the flow region: along segment AB and CD, complex potential is real,  $\psi = 0$ , and along segment BC, complex potential is imaginary,

$\phi = 0$ . Now the complex potential function will be evaluated by applying Cauchy's

integral formula,

$$f(a) = \frac{1}{2\pi i} \oint_C \frac{f(z)dz}{z - a} \quad (5.5)$$

where  $f(z)$  is an analytic function within and on a closed contour  $C$  of a simply connected region  $R$ , and point  $a$  is interior to  $C$ . Here, the value of function in the lower half-plane is evaluated

$$\frac{\omega(z,t)}{\sqrt{z^2 - b^2}} = -\frac{1}{\pi i} \int_{-\infty}^{-b} \frac{\omega(\zeta,t) d\zeta}{\zeta - z} \quad (5.6)$$

where

$$\omega(\zeta,t) = \frac{\phi(\zeta,t)}{\sqrt{\zeta^2 - b^2}} \quad (5.7)$$

The potential is defined in terms of the hydraulic conductivity and head as

$$\phi(\zeta,t) = -k_h h(\zeta,t) \quad (5.8)$$

where head fluctuation is represented by

$$h(\zeta,t) = h_0 + h_1 \sin(\omega t) \quad (5.9)$$

Equations 5.6, 5.7, 5.8, and 5.9 lead to

$$\omega(z,t) = -\frac{k_h \sqrt{z^2 - b^2}}{\pi i} \left\{ h_0 \int_{-\infty}^{-b} \frac{d\zeta}{\sqrt{\zeta^2 - b^2} (\zeta - z)} + h_1 \sin(\omega t) \int_{-\infty}^{-b} \frac{d\zeta}{\sqrt{\zeta^2 - b^2} (\zeta - z)} \right\} \quad (5.10)$$

The solution of the integral in Equation 5.10 is listed by Petit Bois (1961)

$$\int \frac{dx}{(r^2 x + pq) \sqrt{r^2 x^2 - q^2}} = -\frac{1}{qr \sqrt{r^2 - p^2}} \arcsin \frac{prx + qr}{r^2 x + pq} \quad (5.11)$$

If  $r = 1$ ,  $q = b$  and  $p = -z/b$ , the integral is evaluated as

$$\int_{-\infty}^{-b} \frac{d\zeta}{\sqrt{\zeta^2 - b^2} (\zeta - z)} = -\frac{1}{\sqrt{b^2 - z^2}} \left( \arcsin \left( -\frac{z}{b} \right) - \frac{\pi}{2} \right) \quad (5.12)$$

Equation 5.12 is substituted into Equation 5.10 to obtain the complex potential



$$\omega(z, t) = -\frac{k_h \sqrt{z^2 - b^2}}{\pi i} \left\{ \begin{aligned} & \frac{-1}{\sqrt{b^2 - z^2}} h_0 \left( \frac{\pi}{2} - \arcsin\left(\frac{z}{b}\right) \right) \\ & + \frac{-1}{\sqrt{b^2 - z^2}} h_1 \sin(\omega t) \left( \frac{\pi}{2} - \arcsin\left(\frac{z}{b}\right) \right) \end{aligned} \right\} \quad (5.13)$$

where

$$\arccos\left(\frac{z}{b}\right) = \frac{\pi}{2} - \arcsin\left(\frac{z}{b}\right) \quad (5.14)$$

so  $\omega(z, t)$  is reduced to,

$$\omega(z, t) = -\frac{k}{\pi} (h_0 + h_1 \sin(\omega t)) \arccos\left(\frac{z}{b}\right) \quad (5.15)$$

and

$$z = b \cos \frac{\omega(z, t) \pi}{k_h (h_0 + h_1 \sin(\omega t))} \quad (5.16)$$

Equation 5.16 can be separated into real and imaginary parts by using the following properties  $z = x + iy$  and  $\omega(z, t) = \phi(z, t) + i\psi(z, t)$ . These properties lead to Equation 5.16 becoming

$$\cos(\omega) = \cos \phi \cos \psi - i \sin \phi \sin \psi \quad (5.17)$$

and

$$x = b \cos \phi_1 \cosh \psi_1 \quad (5.18)$$

$$y = -b \sin \phi_1 \sinh \psi_1 \quad (5.19)$$

where

$$\phi_1 = \frac{\phi \pi}{k_h (h_0 + h_1 \sin(\omega t))} \quad (5.20)$$

$$\psi_1 = \frac{\psi \pi}{k_h (h_0 + h_1 \sin(\omega t))} \quad (5.21)$$

The streamline and equipotential line equations are derived from the relationships:

$\sin^2 \phi_1 + \cos^2 \phi_1 = 1$  and  $\cosh^2 \psi_1 - \sinh^2 \psi_1 = 1$  with the results:

$$\frac{x^2}{b^2 \cosh^2 \psi_1} + \frac{y^2}{b^2 \sinh^2 \psi_1} = 1 \quad (5.22)$$

which gives ellipses for the stream lines, and

$$\frac{x^2}{b^2 \cos^2 \phi_1} - \frac{y^2}{b^2 \sin^2 \phi_1} = 1 \quad (5.23)$$

which gives hyperbolas for the equipotential lines. Equations 5.22 and 5.23 are used to draw flow nets for a confined flow under a levee on soil of infinite depth aquifer with a fluctuating reservoir boundary.

The velocity distribution can be evaluated by taking the derivative of the complex potential given by Equation 5.15:

$$\frac{d}{dz} \omega(z, t) = -\frac{k_h}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{d}{dz} \arccos\left(\frac{z}{b}\right) \quad (5.24)$$

$$\frac{d}{dz} \omega(z, t) = -\frac{k_h}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{-1}{\sqrt{1 - \frac{z^2}{b^2}}} \frac{1}{b} \quad (5.25)$$

The relationships  $\frac{d}{dz} \omega(z, t) = u + iv$  where  $u$  and  $v$  are the velocity components in the x

and y directions, respectively, give the result

$$u(z, t) + iv(z, t) = \frac{k_h}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{1}{\sqrt{b^2 - z^2}} \quad (5.26)$$

As mentioned above  $z$  is a complex variable so that Equation 5.26 becomes:

$$u(z, t) + iv(z, t) = \frac{k_h}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{1}{\sqrt{b^2 - x^2 - i2xy + y^2}} \quad (5.27)$$

Along the landside of levee, along CD in Fig. 5.1,  $y = 0$  is substituted into Equation 5.27 to obtain the horizontal component of velocity:

$$u(x,0,t) = \frac{k_h}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{1}{\sqrt{b^2 - x^2}} \quad (5.28)$$

and the vertical component of the velocity is derived by multiplying numerator and denominator of Equation 5.28 by complex number,  $i = \sqrt{-1}$  to obtain

$$v(x,0,t) = \frac{k_h}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{1}{\sqrt{x^2 - b^2}} \quad (5.29)$$

The exit gradient,  $i_e$ , is evaluated by using the relationship,  $v = k_h i_e$

$$i_e = \frac{1}{\pi} (h_0 + h_1 \sin(\omega t)) \frac{1}{\sqrt{x^2 - b^2}} \quad (5.30)$$

Equation 5.30 is used to calculate the exit gradient along the landside of the levee where  $x \geq b$ . This equation implies that in the vicinity of  $x = b$ , the toe of the levee as seen in Fig. 5.1, the exit gradient is unbounded, and there exists in this area the danger of piping. Of course, as the velocity becomes greater, Darcy's equation is no longer valid so a prediction of an infinite velocity at the levee toe is not literally true. Still the levee toe is a vulnerable location for high velocity and piping.

### 5.3 Construction of Transient Flow Nets for Finite Depth Aquifers

Flow in a finite depth aquifer is considered. Equations to draw transient flow nets for a confined flow under a levee on soil of finite depth aquifer are developed. The strip flow region in the  $z$ -plane is mapped onto the lower  $\zeta$  half plane (Fig. 5.2). The Schwartz-Christoffel formula is used for the transformation (Harr, 1962):

$$z = Mk^2 \int_0^{\zeta} \frac{d\zeta}{1 - k^2 \zeta^2} \quad (5.31)$$

where  $M$  and  $k$  are some numbers and will be determined after further analysis. The integral in Equation 5.31 is evaluated as

$$z = \frac{M}{2k} \ln \frac{1+k\zeta}{1-k\zeta} \quad (5.32)$$

The length of the base, BC is  $2b$ . For  $\zeta = \pm 1$ ,  $z = \pm b$ , then

$$l = \frac{M}{2k} \ln \frac{1+k}{1-k} \quad (5.33)$$

Walking around the point  $\zeta = 1/k$  in the lower half plane in Fig. 5.2 corresponds to jumping from segment CD to DE in the  $z$ -plane, and gives an increase of  $-\pi i$ . This value also corresponds to the change in the imaginary part of  $z$ , from  $y = 0$  to  $y = -B$ , which is the thickness of the aquifer. Therefore,

$$\Delta z = -Bi = -\frac{M}{2k} \pi i \quad (5.34)$$

So,  $M$  is found as

$$M = \frac{2kB}{\pi} \quad (5.35)$$

Then,  $M$  is substituted into Equation 5.33 to obtain

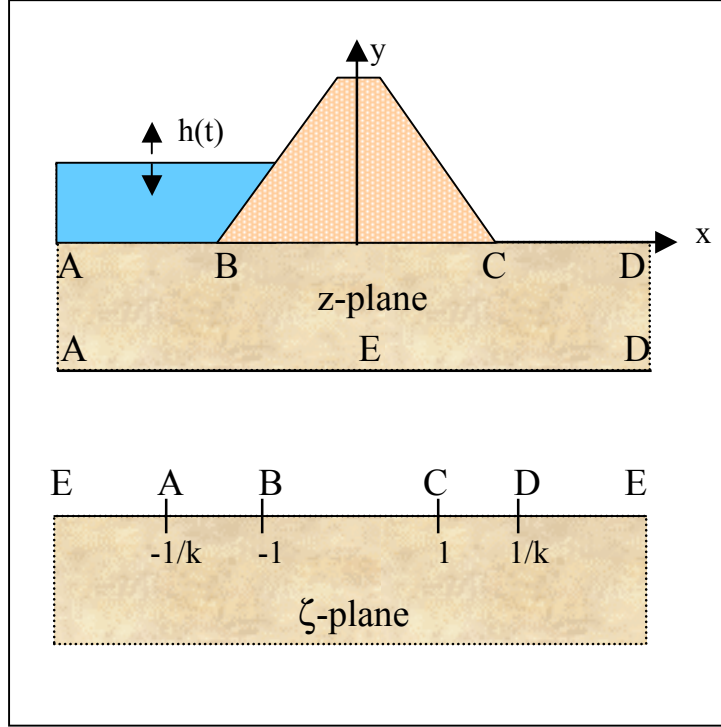
$$l = \frac{B}{\pi} \ln \frac{1+k}{1-k} \quad (5.36)$$

and  $k$  is found as

$$k = \tanh \frac{\pi b}{2B} \quad (5.37)$$

In order to solve for  $z$ , we use elliptic integrals. The elliptic integral of the first kind in canonical form is

$$u = \int_0^{\zeta} \frac{d\zeta}{\sqrt{(1-\zeta^2)(1-k^2\zeta^2)}} \quad (5.38)$$



**Fig. 5.2 Flow region in z-plane and  $\zeta$ -plane.**

where the elliptic sine is also introduced as

$$\zeta = snu \quad (5.39)$$

and

$$u = \frac{2K\omega}{k_h h(x,t)} \quad (5.40)$$

where  $K$  is complete elliptic integral of the first kind with modulus  $m$ ,  $k_h$  is hydraulic conductivity of the aquifer, and

$$h(x,t) = h_0 + h_1 \sin(\omega t) \quad (5.41)$$

Then  $z$  is developed as

$$z = \frac{B}{\pi} \ln \frac{1 + k snu}{1 - k snu} \quad (5.42)$$

Equation 5.42 is differentiated and evaluated as

$$z' = \frac{B}{\pi} 2k \frac{cnu}{dnu} \quad (5.43)$$

where elliptic functions;  $cnu = \sqrt{1 - sn^2 u}$  and  $dnu = \sqrt{1 - k^2 sn^2 u}$ , and the ratio  $\frac{cnu}{dnu}$  is

developed into the trigonometric series as

$$z = \frac{4B}{\pi} \left\{ \frac{\cos\left(\frac{\pi\omega}{k_h h(x,t)}\right)}{\sinh\left(\frac{\pi K'}{2K}\right)} + \frac{\cos\left(\frac{3\pi\omega}{k_h h(x,t)}\right)}{3 \sinh\left(\frac{3\pi K'}{2K}\right)} + \frac{\cos\left(\frac{5\pi\omega}{k_h h(x,t)}\right)}{5 \sinh\left(\frac{5\pi K'}{2K}\right)} + \dots \right\} \quad (5.44)$$

where  $B$  is the depth of aquifer,  $K'$  is the complete elliptic integral of the first kind with complementary modulus  $m'$  and  $K$  is the complete elliptic integral of the first kind with modulus  $m$ . Harr (1962) presents a table for complete elliptic integrals of the first kind.

As mentioned before,  $\omega(z) = \phi + i\psi$  is a function of the complex variable,

$z = x + iy$ , where  $\phi$  and  $\psi$  are constants representing constant potential and stream

functions. Equation 5.48 can be separated into its real and imaginary parts:

$$x = \frac{4B}{\pi} \left\{ \frac{\cos\left(\frac{\pi\phi}{k_h h(x,t)}\right) \cosh\left(\frac{\pi\psi}{k_h h(x,t)}\right)}{\sinh\left(\frac{\pi K'}{2K}\right)} + \frac{\cos\left(\frac{3\pi\phi}{k_h h(x,t)}\right) \cosh\left(\frac{3\pi\psi}{k_h h(x,t)}\right)}{3 \sinh\left(\frac{3\pi K'}{2K}\right)} + \dots \right\} \quad (5.45)$$

$$y = -\frac{4B}{\pi} \left\{ \frac{\sin\left(\frac{\pi\phi}{k_h h(x,t)}\right) \sinh\left(\frac{\pi\psi}{k_h h(x,t)}\right)}{\sinh\left(\frac{\pi K'}{2K}\right)} + \frac{\sin\left(\frac{3\pi\phi}{k_h h(x,t)}\right) \sinh\left(\frac{3\pi\psi}{k_h h(x,t)}\right)}{3 \sinh\left(\frac{3\pi K'}{2K}\right)} + \dots \right\} \quad (5.46)$$

Along the boundary CD of Fig. 5.1, the velocity is

$$v = \frac{k_h h(x,t) \pi}{4KB} \frac{\cosh\left(\frac{\pi b}{2B}\right)}{\sqrt{\sinh\left(\frac{\pi(b+x)}{2B}\right) \sinh\left(\frac{\pi(x-b)}{2B}\right)}} \quad (5.47)$$

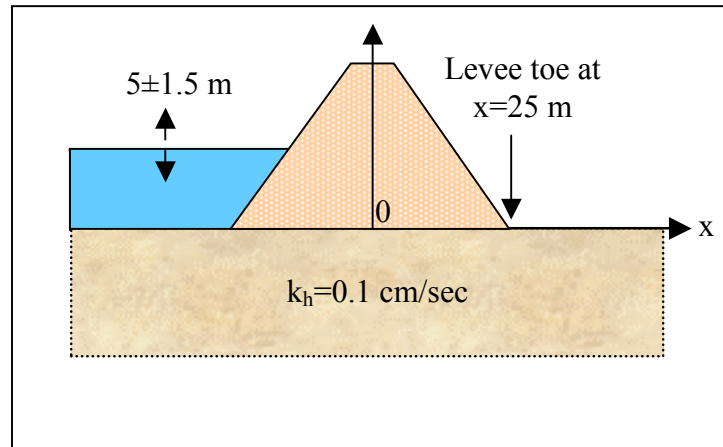
Then, the exit gradient,  $i_e$ , is evaluated by using the relationship,  $v = k_h i_e$ , so that

$$i_e = \frac{h(x,t) \pi}{4KB} \frac{\cosh\left(\frac{\pi b}{2B}\right)}{\sqrt{\sinh\left(\frac{\pi(b+x)}{2B}\right) \sinh\left(\frac{\pi(x-b)}{2B}\right)}} \quad (5.48)$$

In conclusion, Equations 5.45 and 5.46 are used to draw flow nets for a confined flow under a levee on soil of finite depth aquifer with a fluctuating reservoir boundary. Equation 5.48 is used to calculate the exit gradient along the landside of the levee.

#### 5.4 Results and Discussion

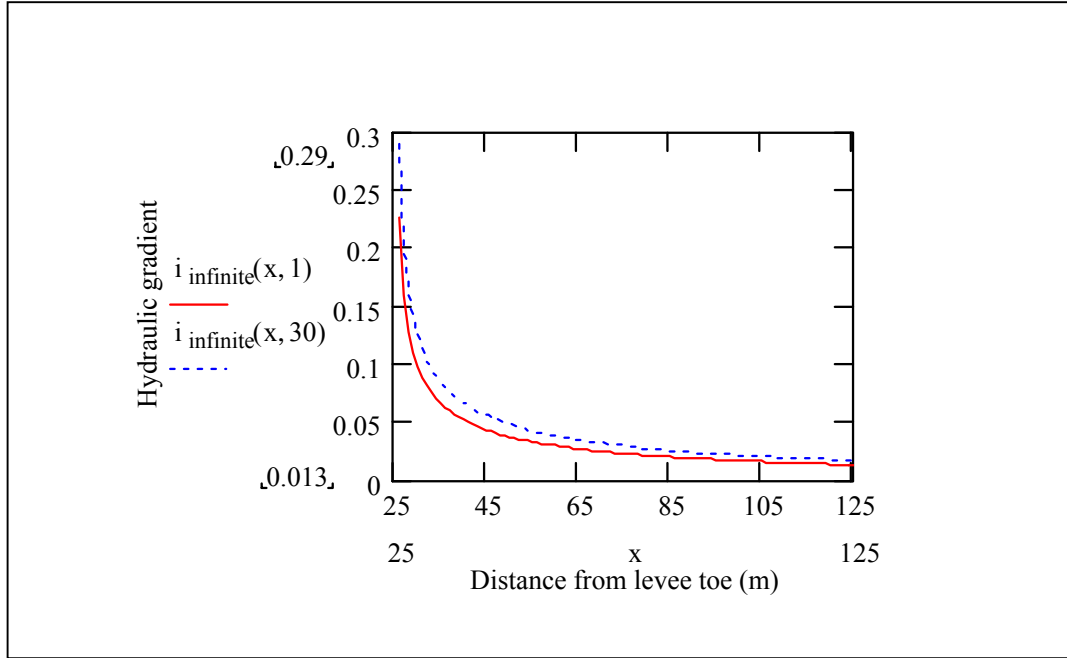
Exit gradients on the landside of the levee on an infinite depth aquifer can be calculated using Equation 5.30. A schematic view of the problem is in Fig. 5.3.



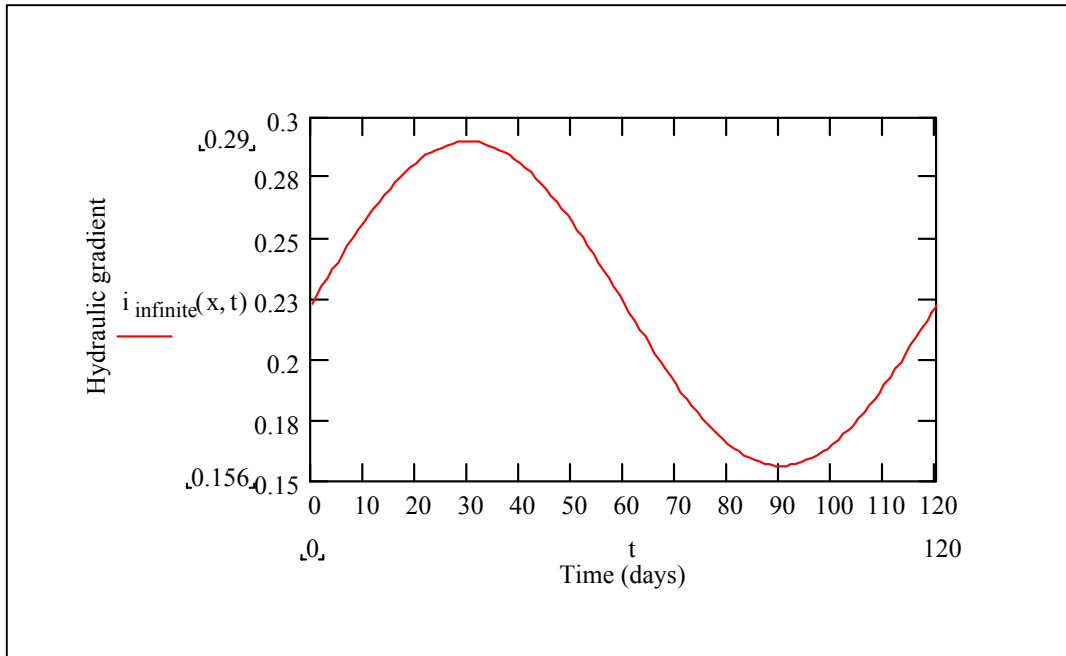
**Fig. 5.3 A schematic view of the problem (not in scale).**

A net head of 5 m, and a fluctuation of 1.5 m were selected in the analysis. The flood duration was selected as 60 days. The initial head of 5 m rises to the peak of 6.5 m at time=30 days, and falls back to 5 m at time=60 days. The base width of the levee was

selected as 50 m. As shown in Equation 5.30, the exit gradient for infinite depth aquifers is not dependent on the thickness of the aquifer. The hydraulic gradient distribution for the confined flow in a soil of an infinite depth aquifer is shown in Fig. 5.4 and 5.5.



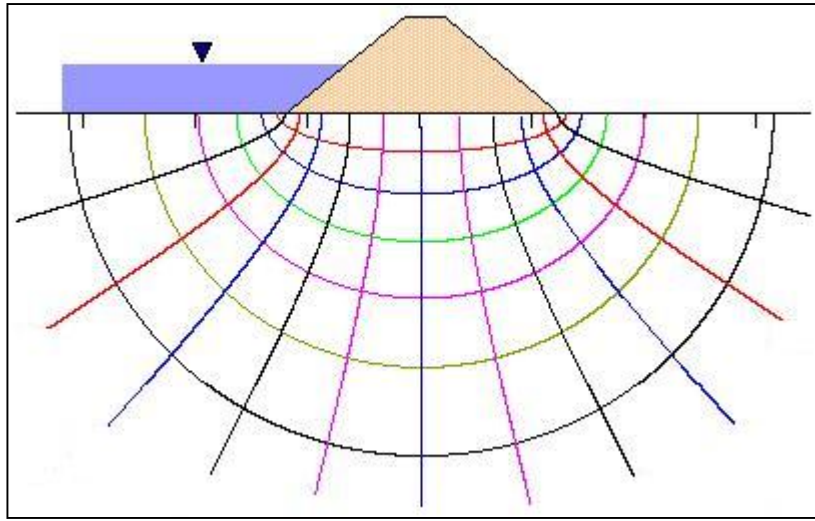
**Fig. 5.4 Transient exit gradient at  $t=1$  day and  $t=30$  days on landside of the levee on a soil of infinite depth aquifer.**



**Fig. 5.5 Transient exit gradient at the levee toe on a soil of infinite depth aquifer.**

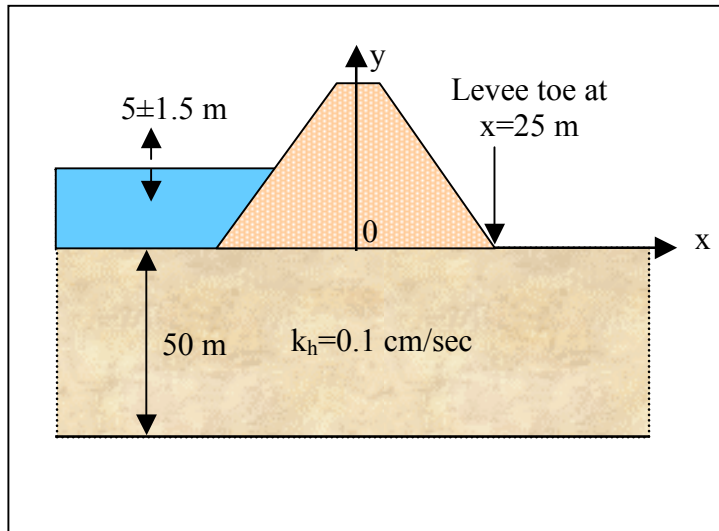


A transient flow net for infinite depth aquifers can be drawn by using Equation 5.22 and 5.23. Figure 5.6 shows the flow net for horizontal and vertical hydraulic conductivity of  $k_h = 0.1$  cm/sec, and time,  $t = 30$  days, when the head fluctuation makes its peak,  $h = 6.5$  m in the river. Although transient flow net equations were used to draw the flow net, there exists only one flow net for a certain cross section of levee. In other words, the shape of the flow net does not change with time but the numerical values of the streamlines and equipotential lines change with time.

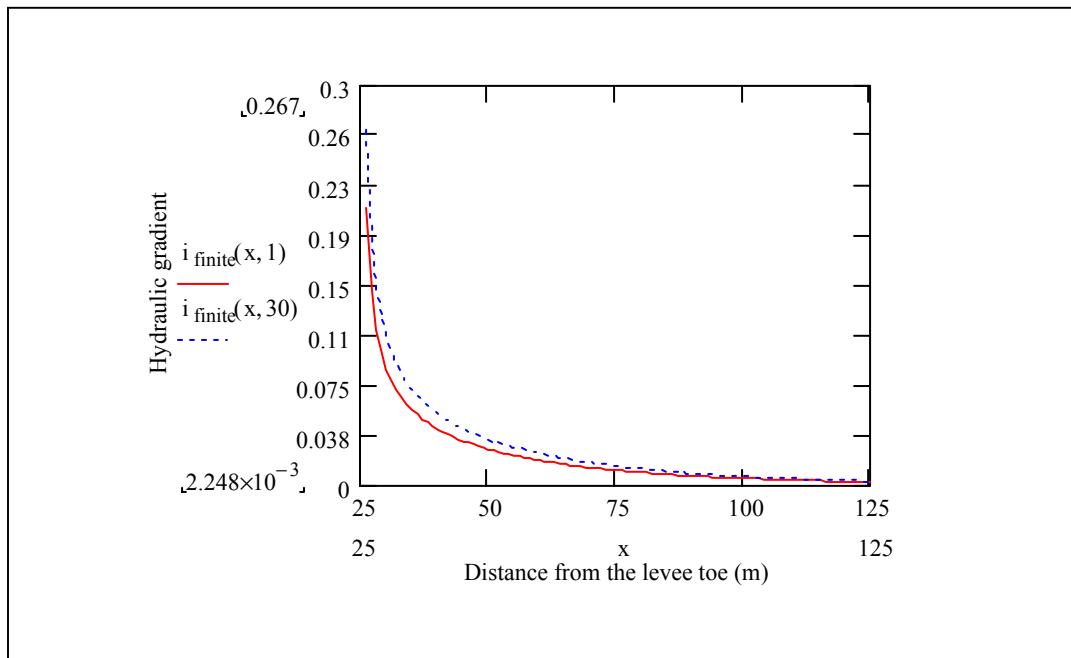


**Fig. 5.6 Transient flow net for infinite depth aquifers,  $h=6.5$  m in the river,  $k=0.1$  cm/sec,  $t=30$  days.**

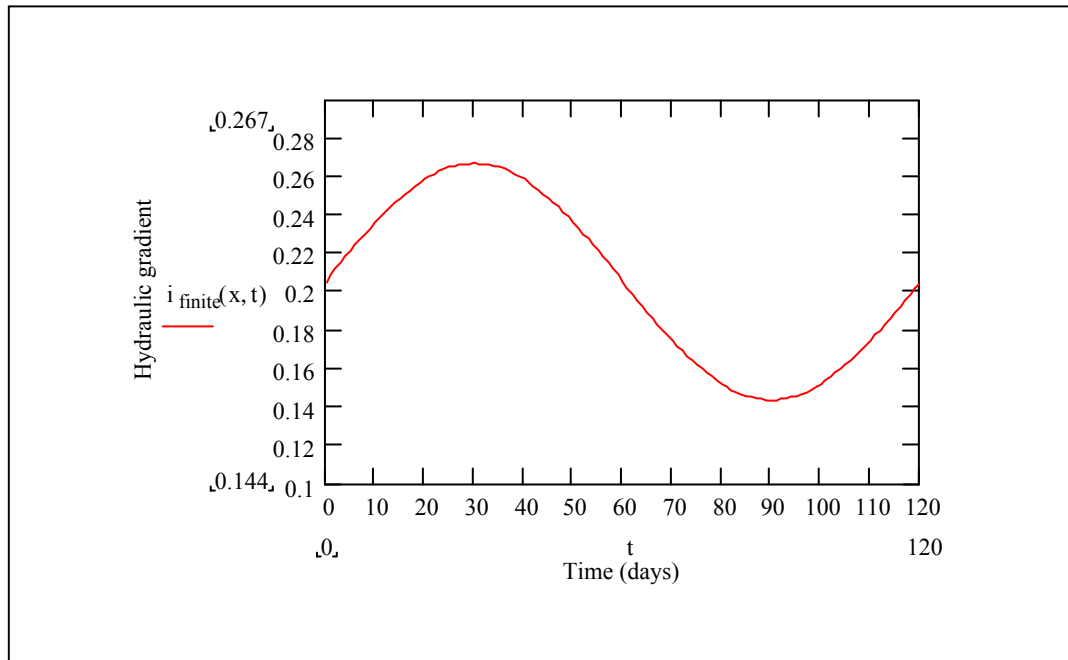
The aquifer thickness for the finite depth aquifer case is taken as 50 m. A scheme of the problem is shown in Fig. 5.7. Equation 5.48 is used to calculate the hydraulic gradient distribution for the confined flow in a soil of finite depth aquifer. The results are shown in Fig. 5.8 and 5.9. If a scaled flow net is drawn, the exit gradient shown in Fig. 5.8 is reasonable, and it fluctuates depending on the fluctuations in the river as shown in Fig. 5.9.



**Fig. 5.7** A schematic view of the problem (not in scale).

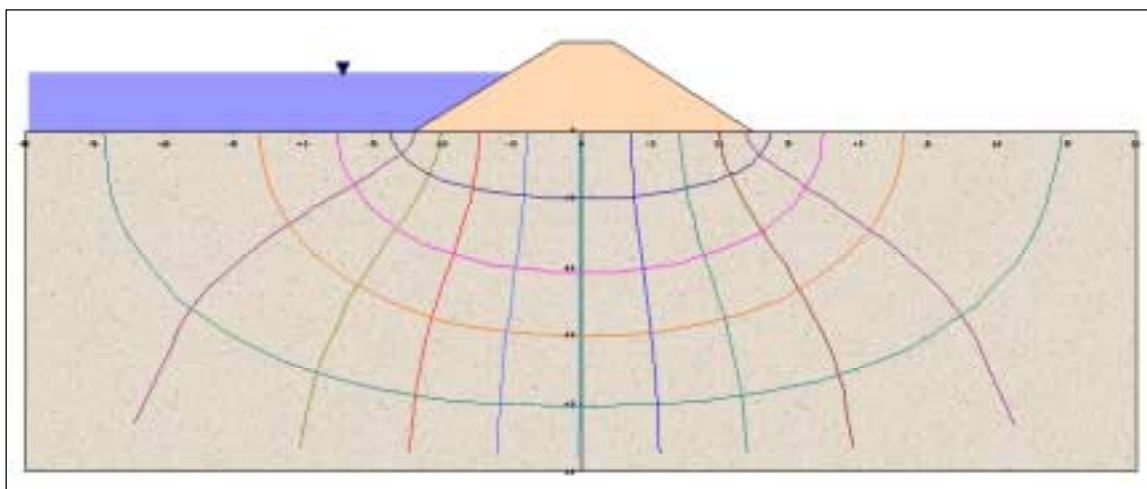


**Fig. 5.8** Transient exit gradient at  $t=1$  day and  $t=30$  days on landside of the levee on a soil of finite depth aquifer.



**Fig. 5.9 Transient exit gradient at the levee toe on a soil of finite depth aquifer.**

A transient flow net for finite depth aquifers can be drawn by using Equations 5.45 and 5.46. Figure 5.10 shows the flow net for vertical and horizontal hydraulic conductivity,  $k_h = 0.1$  cm/sec, and time,  $t = 30$  days, when the head fluctuation makes its peak,  $h = 6.5$  m in the river.



**Fig. 5.10 Transient flow net for finite depth aquifers,  $h=6.5$  m in the river,  $k=0.1$  cm/sec,  $t=30$  days, aquifer depth=50 m.**

Again, although transient flow net equations were used to draw the flow net, there exists only one flow net for a certain cross section of levee. However, the numerical values assigned to equipotential and flow lines change with time depending on the river head fluctuations

## **5.5 Summary**

In this chapter, time dependent flow nets were constructed. Two solutions were provided; one for infinite depth aquifers and one for finite depth aquifers. The methodologies given by Polubarinova-Kochina (1962) were followed in both solutions. The assumptions and the conditions in her solutions were maintained for the coordinate  $y = 0$ ; a downward vertical flow on the riverside of the levee, a horizontal flow under the levee, and an upward vertical flow at the landside of the levee.

The flow nets were constructed for isotropic flow conditions. Exit gradients were also evaluated. The results look very reasonable. As noted before, the geometry of the flow nets does not change with time, however the numerical values assigned to the equipotential lines and flow lines change with time due to head fluctuations. The governing equations to the two-dimensional transient flow problem did not contain storage terms so the streamlines and equipotential lines responded instantaneously to changes in flood elevation.

The main objective of this chapter was to construct transient flow nets. This objective was satisfied. An analytical solution for a transient flow net has not been reported in the literature. The solutions presented here could be interesting to the engineering community.

## **5.6 List of Symbols**

$b$  = horizontal distance (L)

$B$  = vertical distance (L)

$\text{cn } u, \text{dn } u, \text{sn } u$  = Jacobian elliptic functions

$f(z)$  = complex function

$h$  = hydraulic head (L)

$h_0$  = initial hydraulic head (L)

$h_1$  = amplitude of the variation from the initial hydraulic head (L)

$i$  = imaginary unit where  $i^2 = -1$

$i_e$  = exit hydraulic gradient

$k_h$  = hydraulic conductivity of soil

$K$  = complete elliptic integral of the first kind with modulus  $m$

$K'$  = complete elliptic integral of the first kind with complementary modulus  $m'$

$M, k, l, \zeta$  = constants used in Schwartz-Christoffel formula

$p, q, r$  = constants used in the solution of an integral (Eqn. 5.11)

$t$  = time (T)

$T$  = time dimension

$u, u(z,t), u(x,t)$  = velocity component in x-direction

$u$  = elliptic integral function

$v, v(z,t)$  = velocity component in y-direction

$x$  = horizontal coordinate (L)

$y$  = vertical coordinate (L)

$\phi$  = potential function

$\psi$  = stream function

$\zeta$  = complex variable

$\omega(z), \omega(z, t)$  = complex potential

$\omega$  = frequency ( $T^{-1}$ )

$z$  = complex variable

## **CHAPTER 6      PERFORMANCE ANALYSIS**

### **6.1      Introduction**

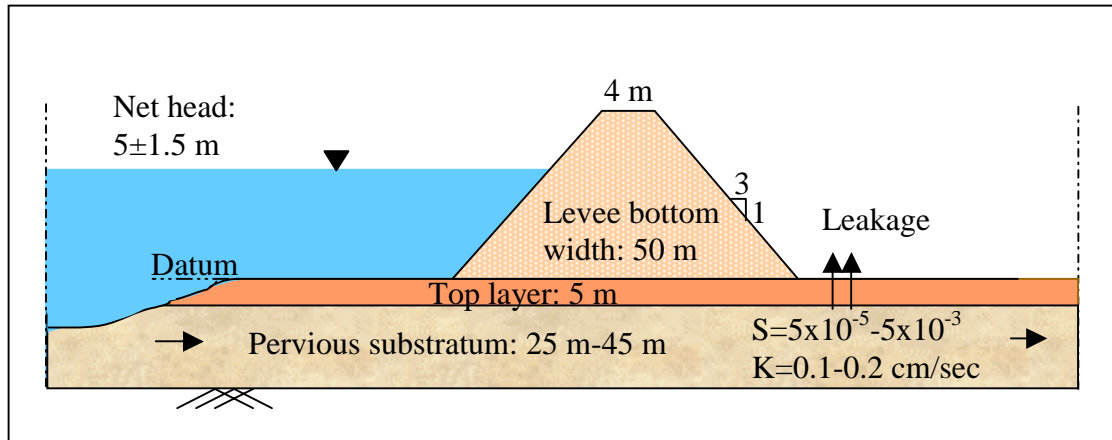
The objective of this chapter was to compare hydraulic head and exit gradient development beneath a levee by the transient flow models developed in Chapters 3 and 4 with commonly used seepage analysis methods. This section also explored whether transient effects are critical to the development of exit hydraulic gradients, which may lead to sand boil formation.

The transient flow model developed in Chapter 3 is applicable to homogeneous confined aquifers while the flow model developed in Chapter 4 is applicable for a leaky confined aquifer. These transient models were compared with the steady-state models: Army Corps EM 1110-2-1913 method and SEEP2D finite element analysis.

Two-dimensional transient flow net analysis was not used for comparisons. The main focus of this research is one-dimensional transient flow study. A comparison of two-dimensional transient flow net analysis with one-dimensional transient flow models would not be applicable.

Performance of the transient flow models was analyzed using the parameters of the cross section of a typical Mississippi Valley confined aquifer. A typical levee section was selected according to the dimensions set in the Department of Army, Engineer Manual, Design and Construction of Levees, EM 1110-2-1913 (2000). The thickness of sandy alluvium under Mississippi River levees changes from 25 m to 45 m. Horizontal hydraulic conductivity of pervious medium is in the range of 0.1-0.2 cm/sec (Turnbull and Mansur 1961). Typical storativity values for confined aquifers are  $5 \times 10^{-3}$ ,  $5 \times 10^{-4}$ ,  $5 \times 10^{-5}$  (Freeze and Cherry, 1979). In 1993, the net hydraulic head of the middle Mississippi River levees during floods were recorded as 4.8 m to 6.7 m above the

landside of the levee (Mansur *et al.* 2000). Therefore, a net head of 5 m, and a fluctuation of 1.5 m are selected in our analysis. The typical levee section with selected aquifer parameters and hydraulic head is shown in Fig. 6.1.



**Fig. 6.1 A typical levee section with selected parameters (not in scale).**

Two sets of comparisons were carried out. The first set of analyses compared the results of underseepage analysis with the transient flow model, the Army Corps EM 1110-2-1913 method, and SEEP2D finite element analysis. The second set of comparisons analyzed the results of seepage analysis with leakage out of a confined aquifer case. This set includes the results of the transient flow model with leakage and SEEP2D finite element analysis. The Army Corps method does not examine a leakage out of a confined aquifer case. Therefore, it is not applicable for the second set of comparisons.

A brief introduction was provided to the Army Corps EM 1110-2-1913 method and SEEP2D finite element software.

- **Army Corps EM 1110-2-1913 method.** The Department of Army, Engineer Manual, EM 1110-2-1913, Design and Construction of Levees (2000) details the mathematical analysis of underseepage and substratum pressure for levees. The equations

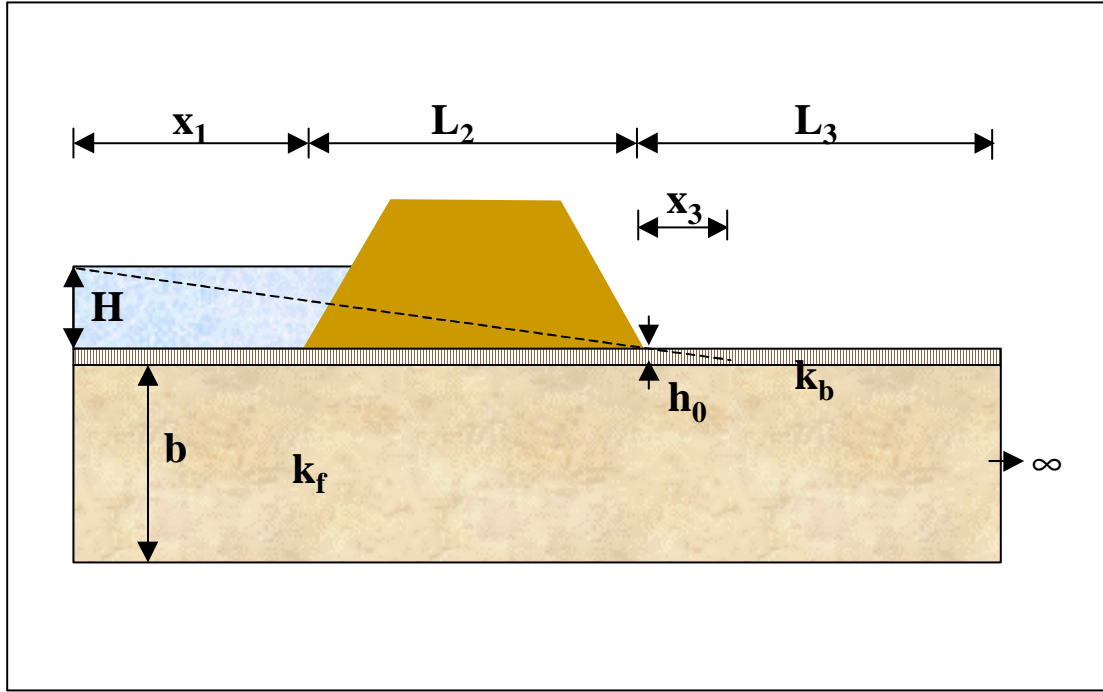


contained in the manual were developed during a study of piezometric data, reported in a technical memorandum, USACE Waterways Experiment Station (WES) TM 3-424 (1956), and confirmed by model studies. The procedures to evaluate the quantity of underseepage, uplift pressures and hydraulic gradients were developed based on closed-form solutions for differential equations of seepage flow presented by Bennett (1946). The equations in this engineer manual were developed considering a two-layer foundation, which is a typical geological condition in Lower Mississippi River Valley. The following simplifying assumptions were set in this seepage analysis (Engineer Manual, EM 1110-2-1913):

- “a. seepage may enter the pervious substratum at any point in the foreshore (usually at riverside borrow pits) and/or through the riverside top stratum,
- b. flow through the top stratum is vertical,
- c. flow through the pervious substratum is horizontal,
- d. the levee and the portion of the top stratum beneath it is impervious,
- e. all seepage is laminar.”

The equations are presented for several cases: no top stratum, impervious top stratum both riverside and landside, impervious riverside top stratum and no landside top stratum, impervious landside top stratum and no riverside top stratum, semipervious riverside top stratum and no landside top stratum, semipervious landside top stratum and no riverside top stratum, semipervious top stratum both riverside and landside. Two more cases were added by Cunney *et al.* (1989) in a Technical Report REMR-GT-13. These cases are: impervious riverside top stratum with semipervious landside top stratum and semipervious riverside top stratum with impervious landside top stratum. In this chapter, out of these nine cases, the most critical case, which is the seventh case listed in EM

1110-2-1913, semipervious top stratum at riverside and landside of levee with a pervious substratum was considered for analysis purpose. A cross-section of the levee with required parameters is shown in Fig. 6.2.



**Fig. 6.2 Basic scheme of levee with design parameters as presented in the Army Corps EM 1110-2-1913.**

The hydrostatic head beneath the top stratum on the landside toe of levee,  $h_0$  is calculated as

$$h_0 = H \left( \frac{x_3}{x_1 + L_2 + x_3} \right) \quad (6.1)$$

where  $x_1$  is effective length of riverside blanket,  $L_2$  is base width of levee, and  $x_3$  is distance from the landside levee toe to the effective seepage exit. If  $L_3$ , landward extent of top stratum measured from landside levee toe, is considered as it goes to infinity, then  $x_3$  is estimated as

$$x_3 = \frac{1}{c} \quad (6.2)$$

$$c = \sqrt{\frac{k_b}{k_f z_b b}} \quad (6.3)$$

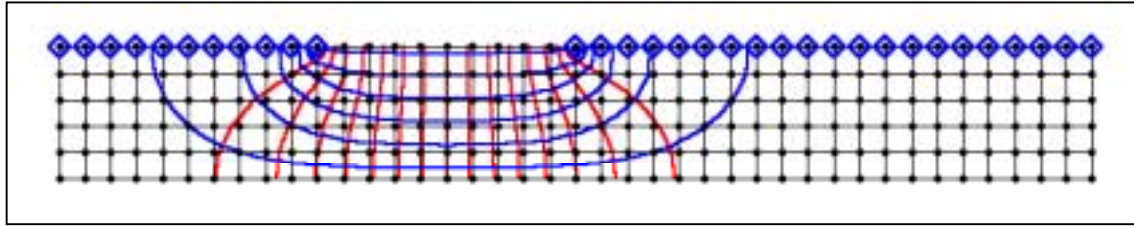
where  $k_b$  is vertical hydraulic conductivity of the top stratum,  $k_f$  is horizontal hydraulic conductivity of the pervious layer,  $z_b$  is thickness of the top stratum, and  $b$  is thickness of the pervious layer. Then, head beneath the top stratum at distance  $x$  from landside levee toe is estimated as

$$h_x = h_0 e^{-cx} \quad (6.4)$$

The hydraulic gradient through the top stratum at the landside of the levee is estimated as

$$i_x = \frac{h_x}{z_b} \quad (6.5)$$

- SEEP2D Seepage Analysis Model.** The SEEP2D software was developed by USACE Waterways Experiment Station to model a variety of problems including seepage. In this research, the SEEP2D model is used in conjunction with the GMS (Groundwater Modeling System). GMS was developed by the Brigham Young University in cooperation with WES. Several conditions can be modeled by using SEEP2D. These conditions include isotropic/anisotropic soil properties, confined/unconfined flow profile models, saturated/unsaturated flow for unconfined profile models, confined flow for plan models, and heterogeneous soil conditions. SEEP2D cannot model transient or time varying problems and unconfined plan models. In the modeling process, a finite element mesh is constructed, boundary conditions are defined, hydraulic conductivities are entered, and then the model is run by SEEP2D and viewed by GMS. A partial aquifer modeled by SEEP2D is shown in Fig. 6.3.

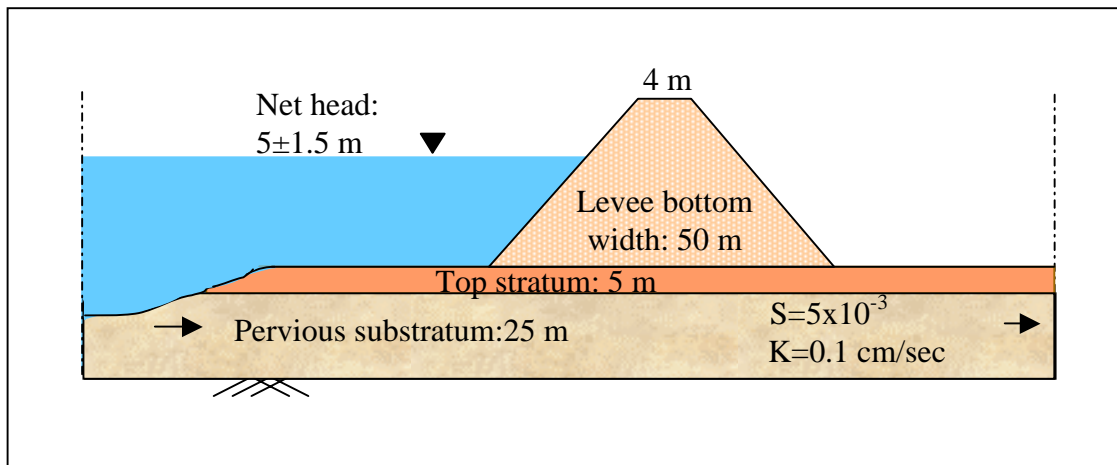


**Fig. 6.3 A sample SEEP2D model.**

This model applied in Fig. 6.3 represents a simple confined flow problem. Constant heads were applied to the boundaries where trapezoid shapes were placed. The other boundaries are “no flow” boundaries where the flow direction is parallel to those regions. Isotropic soil conditions at the soil medium resulted in a familiar flow net for part of the aquifer as shown in Fig. 6.3.

## 6.2 Performance Analysis of Transient Flow Model in a Confined Aquifer

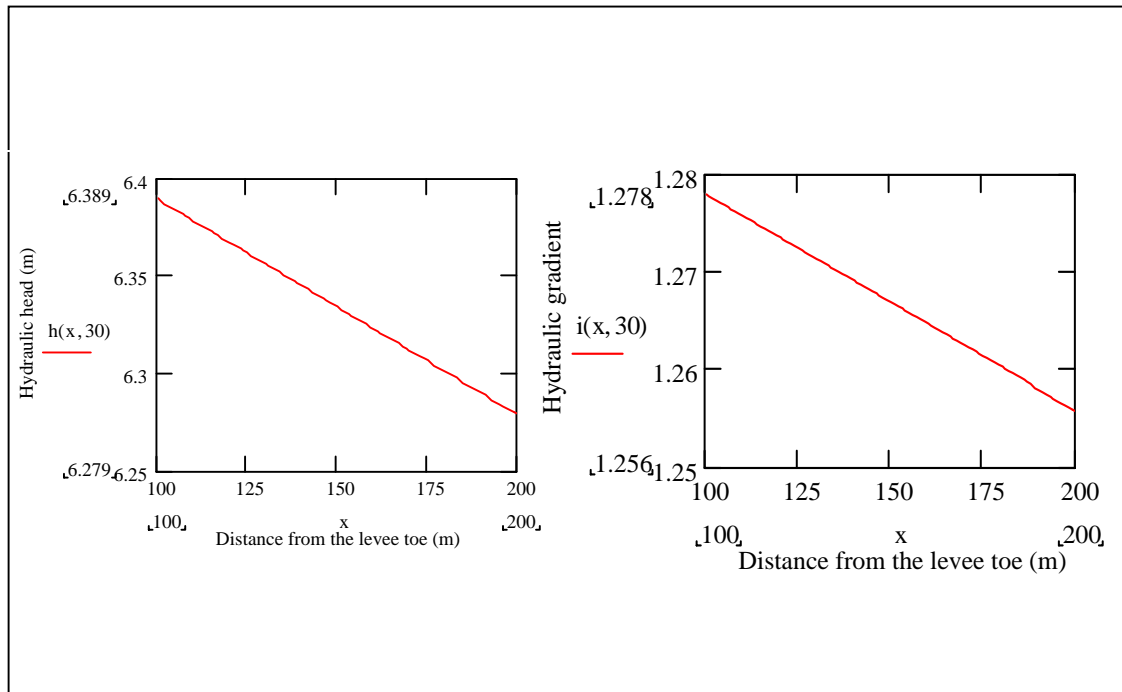
The parameters were selected as shown in Fig. 6.4.



**Fig. 6.4 A levee cross section with selected parameters for performance analysis (not in scale).**

The Laplace transform solution considers seepage through the pervious substratum. The thickness of top stratum is taken into account only for calculating the exit hydraulic gradients. As noted before, the Army Corps method and SEEP2D model

are applicable for steady-state analysis. Therefore a certain time was selected for comparison purpose. The time of the analysis was chosen as 30 days, when the river head makes its peak, which is 6.5 m. Therefore a constant head of 6.5 m was applied for the steady-state methods. In Fig. 6.5, the hydraulic head and hydraulic gradient distribution beneath the levee toe by the Laplace transform solution is shown.

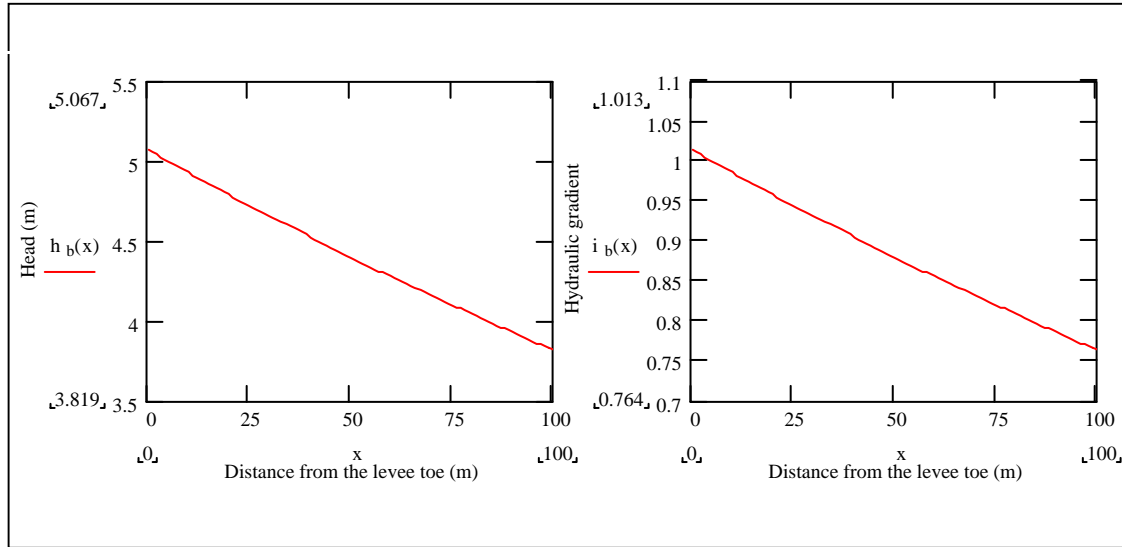


**Fig. 6.5 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer at  $t=30$  days by the transient flow model, Laplace transform method.**

In Fig. 6.5, exit hydraulic gradients were evaluated by dividing the difference in hydraulic heads by the thickness of the top layer, which was chosen as 5 m. The same methodology was followed in the applications of the Army Corps method and SEEP2D model.

The Army Corps solution considers hydraulic conductivity of the top layer (Equation 6.3). Therefore, a vertical hydraulic conductivity of  $1 \times 10^{-4}$  cm/sec was

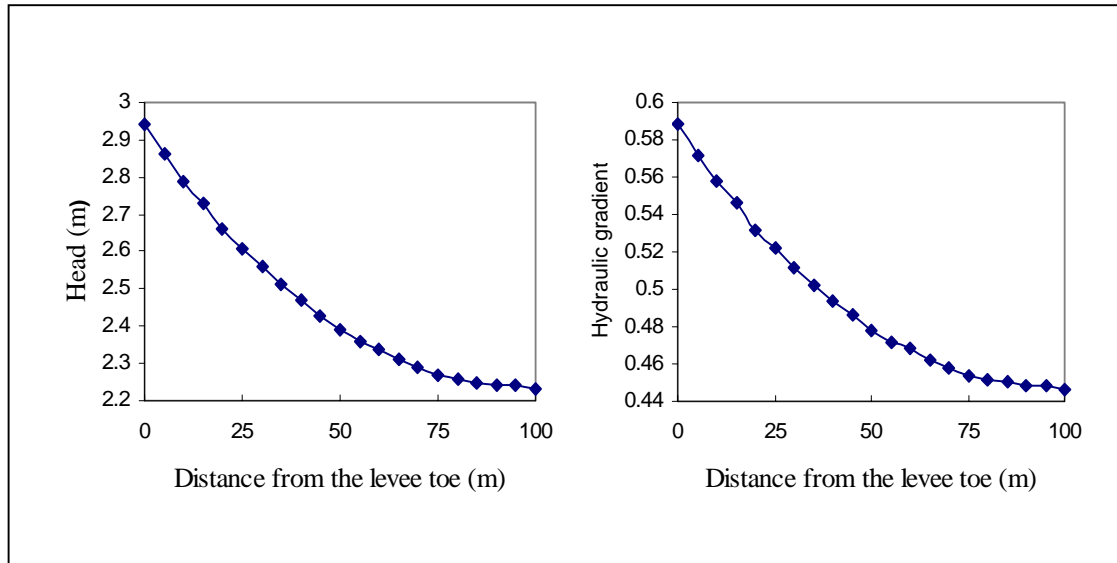
assigned to the top layer of the soil medium for the applications of USACE method. The results are seen in Fig. 6.6.



**Fig. 6.6 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by the Army Corps EM 1110-2-1913 method.**

In the SEEP2D finite element model, an aquifer depth of 30 m with hydraulic conductivities as seen in Fig. 6.4 were defined. Hydraulic head development at 5 m below the landside levee and hydraulic gradients through the landside levee are plotted in Fig. 6.7. The results presented in Figures 6.5 through 6.7 are summarized in Table 6.1, which shows that there are significant differences between the results of the methods.

The analytical transient flow model developed by the Laplace transform method showed the most conservative results compared with the Army Corps method and SEEP2D model. The Laplace transform method assumes that seepage flow travels horizontally in an infinite flow medium. The model does not allow any upward leakage from the flow medium. In addition, as presented in Chapter 3, hydraulic head fluctuations dissipate very slowly. Therefore, high hydraulic gradients were calculated through the top layer.



**Fig. 6.7 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by SEEP2D modeling.**

**Table 6.1 Hydraulic head and gradient beneath the levee for a confined aquifer by various methods.**

Methods	$h_{\text{levee toe}} \text{ (m)}$	$h_{100 \text{ m}} \text{ (m)}$	$i_{\text{levee toe}}$	$i_{100 \text{ m}}$
Transient flow model	6.39	6.28	1.28	1.26
The Army Corps method	5.07	3.82	1.01	0.76
SEEP2D model	2.94	2.23	0.59	0.45

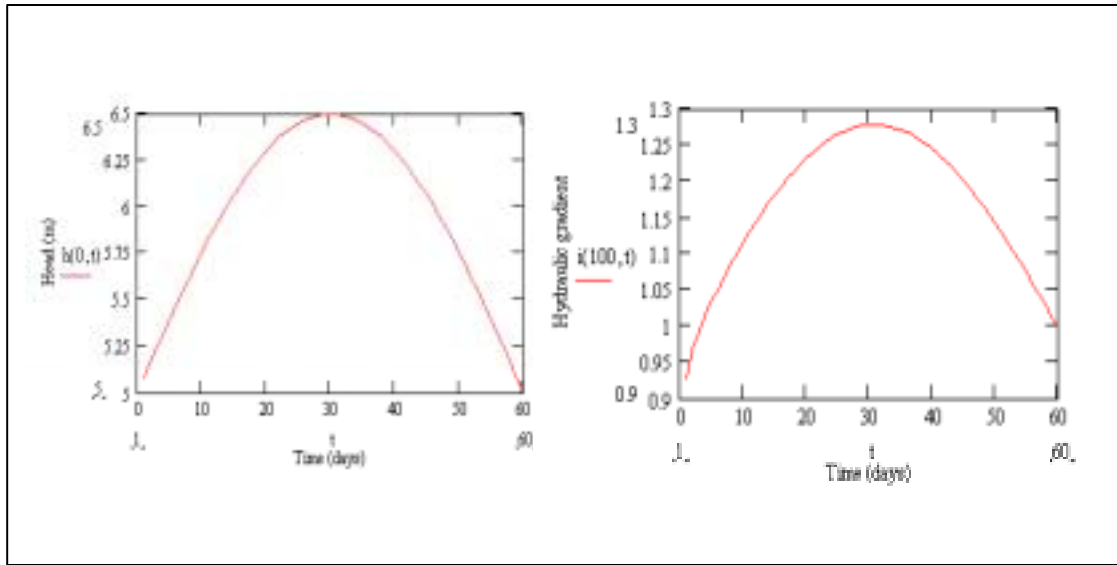
The SEEP2D finite element model was run under the confined aquifer medium, however the program allows a portion of seepage flow to exit vertically through the top blanket. This upward seepage reduced hydraulic head development on the landside of the levee, and reduces the hydraulic gradient through the top layer.

Gabr *et al.* (1995) presented a study on the comparison between finite element analysis and simplified analysis of levee underseepage. They used LEVSEEP and LEVEEMSU computer programs for simplified analysis of levee underseepage. As discussed in the second chapter, both computer programs were based on Bennett's (1946) analytical solutions and both methods were expected to give results close to those

outlined in Levee Design Manual, EM 1110-2-1913, which is the Army Corps method analyzed in this research. Gabr *et al.* (1995) used PCSEEP and SEEP finite element computer programs in their study. SEEP is an older version of the SEEP2D model used in this dissertation. The researchers found significant differences between the results of LEVSEEP and LEVEMSU and those from the two-dimensional finite element models. They concluded that exit hydraulic gradients predicted from simplified LEVSEEP and LEVEMSU for the cases studied were conservative as compared with those predicted from the finite element model. They noted that there were no available piezometer data for high-water levels to verify the results from the finite element models. They also noted that a comprehensive parameter study and investigation of several case histories were needed before the conclusions they presented could be generalized. Table 6.1 also shows conservative results from the Army Corps method compared with the SEEP2D model.

So far, the comparisons of the flow models were based on steady-state conditions. The Army Corps method and the SEEP2D model can be solved for various heads and the results of these steady-state flow models can be compared with the results of the transient flow model. A flood wave of 60-day duration with a net head of 5 m and a fluctuation of 1.5 m were used for this purpose. The flood wave and corresponding hydraulic gradient development at the levee toe by the Laplace transform method are shown in Fig. 6.8. The hydraulic gradient curve in Fig. 6.8 was divided into certain ranges, and then corresponding head values in the river were calculated. The Army Corps method was solved by using these head values and the range of hydraulic gradients were calculated. The results were presented in Table 6.2.





**Fig. 6.8 Flood wave in the river and hydraulic gradient development at the levee toe by Laplace transform method.**

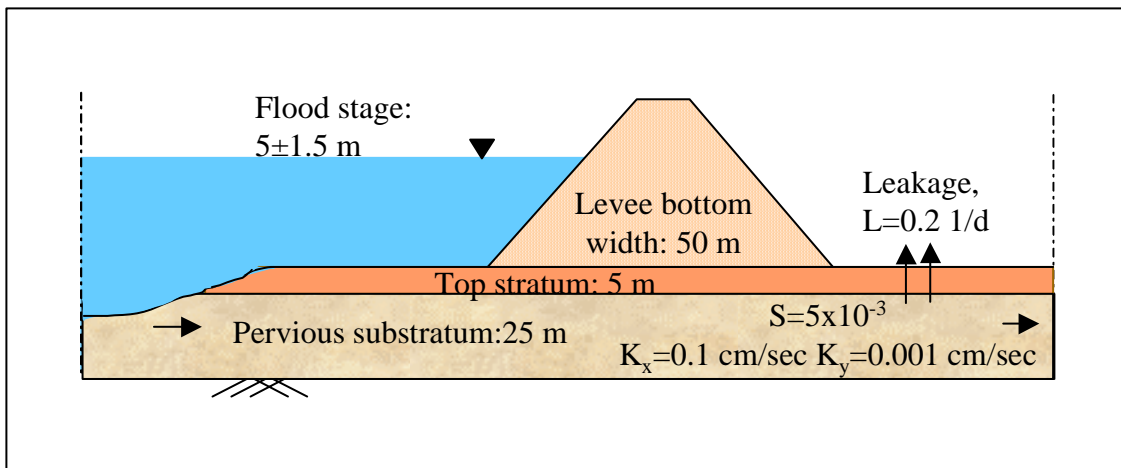
**Table 6.2 Summary of the range of hydraulic gradient and corresponding range of hydraulic head with time duration at the levee toe by Laplace transform method and the Army Corps method.**

Time Range (days)	Duration (days)	Range of Hydraulic Head in the River (m)	Range of Hydraulic Gradient at the Levee Toe	
			Laplace Transform Method	Army Corps Method
1-3	3	5.08-5.24	0.93-0.99	0.79-0.82
4-8	5	5.31-5.61	1.01-1.09	0.83-0.88
9-16	8	5.68-6.12	1.10-1.19	0.89-0.95
17-30	29	6.17-6.50	1.20-1.28	0.96-1.01
31-45		6.50-6.10	1.28-1.20	1.01-0.95
46-53	8	6.00-5.54	1.19-1.10	0.94-0.86
54-59	6	5.46-5.08	1.09-1.01	0.85-0.79
60	1	5.00	1.00	0.78

The SEEP2D model was not used for this analysis because hydraulic gradient at the levee toe by SEEP2D model was significantly lower than the results calculated by the Army Corps and transient flow models (Table 6.1). The analysis shown in Table 6.2 can be useful to determine critical times during a flood. For example, if a hydraulic gradient of 0.85 is considered to be the initiation threshold of a sand boil, according to the transient flow model by Laplace transform solution, the whole high water event is critical, while according to the Army Corps method, the first and the last couple of days of the high water event is not critical. In general, the transient flow model by Laplace transform method and the Army Corps model resulted in close hydraulic gradients, however higher hydraulic gradients were determined by the transient flow model than by the U.S. Army Corps of Engineers method.

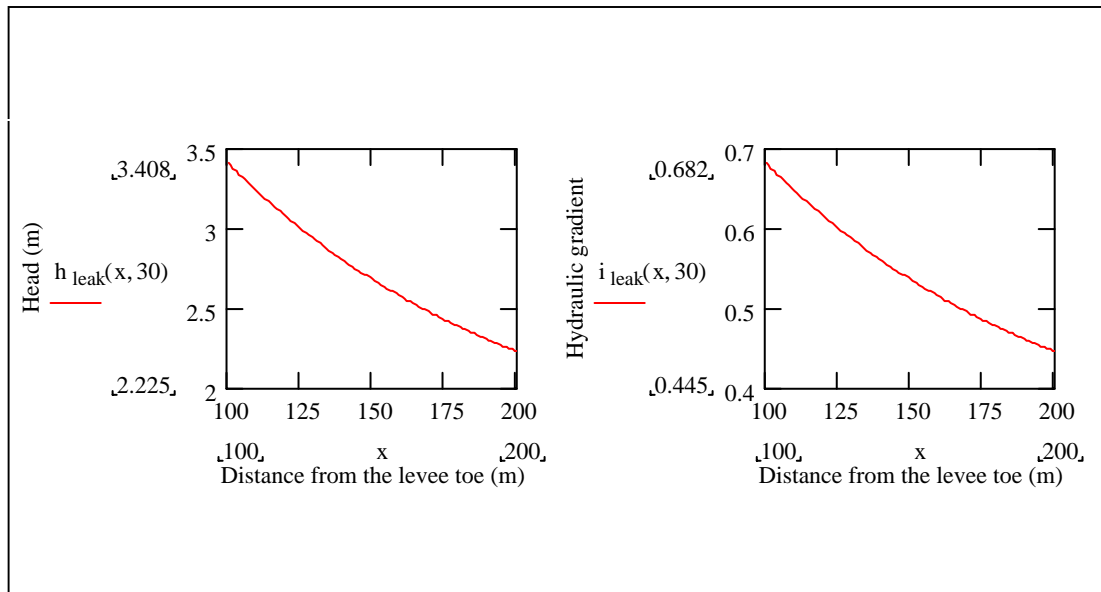
### 6.3 Performance Analysis of Transient Flow Model with Leakage Out of a Confined Aquifer

The parameters were selected as shown in Fig. 6.9.

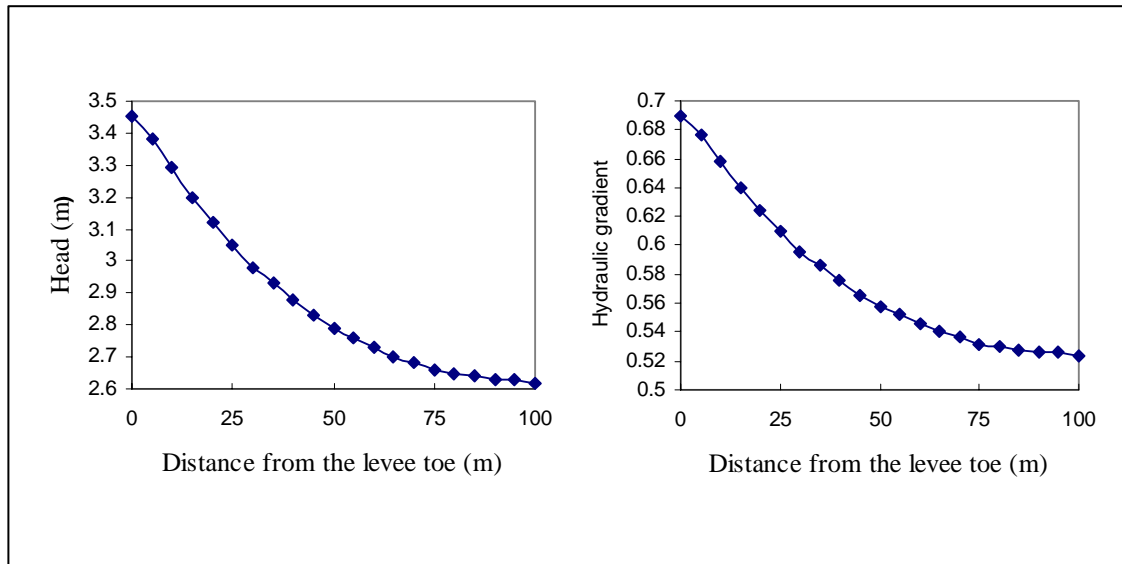


**Fig. 6.9 A levee cross section with selected parameters for performance analysis (not in scale).**

The Laplace transform solution considers seepage through the pervious substratum. In SEEP2D modeling, a constant head boundary was defined at the riverside of the levee and an exit face boundary was defined on the landside of the levee. After the model was run, the flow rates on the landside of the levee were examined. As expected, the highest flow rate occurred at the levee toe. The total flow below the landward levee was averaged through the landside of the levee to find a leakage amount to be used in the transient flow model. This leakage was found to be,  $L=0.2$  1/day per meter of levee. Therefore, a leakage amount of  $L=0.2$  1/day per meter of levee was selected for comparison purposes. In Fig. 6.10, the hydraulic head beneath the landside of the levee, and the hydraulic gradient distribution through the top layer by Laplace transform solution are shown. Hydraulic head and exit gradient distribution beneath the levee by SEEP2D are shown in Fig. 6.11. Table 6.3 summarizes the results presented in Figures 6.10 and 6.11.



**Fig. 6.10 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by the transient flow model, Laplace transform method, with leakage,  $L=0.2$  1/day/m of levee.**



**Fig. 6.11 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by SEEP2D modeling with leakage,  $L=0.2$  1/day/m of levee.**

**Table 6.3 Hydraulic head beneath the levee, and the hydraulic gradient through the top layer for a confined aquifer with leakage,  $L=0.2$  1/day/m of levee, by analytical model and finite element analysis.**

Methods	$h_{\text{levee toe}} \text{ (m)}$	$h_{100 \text{ m}} \text{ (m)}$	$i_{\text{levee toe}}$	$i_{100 \text{ m}}$
Transient flow model	3.41	2.23	0.68	0.45
SEEP2D model	3.45	2.62	0.69	0.52

Table 6.3 shows that hydraulic head and gradient values are closely matched with the transient flow model developed by the Laplace transform method and SEEP2D finite element analysis when there is an upward leakage of 0.2 1/day/m of levee. This agreement can be further investigated by using different leakage quantities. As discussed in the fourth chapter, there are field studies reported by Turnbull and Mansur (1962) on seepage quantities and corresponding exit gradients. The same seepage values can be achieved by the SEEP2D model by changing the driving hydraulic forces and/or

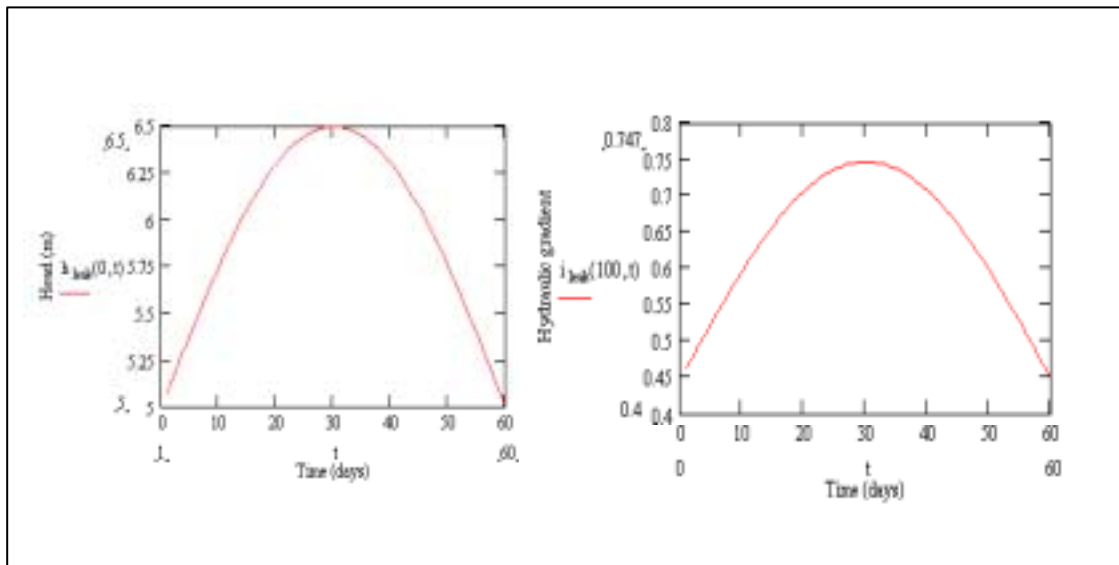
hydraulic conductivity of the medium. The investigated leakage quantities are 5 gal/min /100 ft of levee ( $L=0.14$  1/day/m of levee) and 10 gal/min/100 ft of levee ( $L=0.28$  1/day/m of levee). The results are shown in Table 6.4.

**Table 6.4 Hydraulic head beneath the levee and the hydraulic gradient through the top layer for a confined aquifer with leakage by analytical model and finite element analysis.**

Leakage (1/day/m of levee)	Methods	$h_{\text{levee toe}}$ (m)	$h_{100 \text{ m}}$ (m)	$i_{\text{levee toe}}$	$i_{100 \text{ m}}$
0.14	Transient flow model ( $K_x=0.1$ cm/sec)	3.73	2.50	0.75	0.50
	SEEP2D model ( $K_x=0.063$ cm/sec)	3.49	2.56	0.70	0.51
0.28	Transient flow model ( $K_x=0.1$ cm/sec)	3.10	2.01	0.62	0.40
	SEEP2D model ( $K_x=0.148$ cm/sec)	3.36	2.69	0.68	0.54

Table 6.4 shows that the results from the transient flow model and finite element analysis are still in agreement for different leakage quantities. Here, in SEEP2D analysis, the horizontal hydraulic conductivity of the medium was adjusted in order to get the target leakage quantities at the exit face, which is the landside of the levee. In reality, the hydraulic conductivity of the medium may also change due to the mechanisms involved in the underseepage process. Therefore, adjusting the hydraulic conductivity of the medium in order to get target leakage quantities can be considered as a reasonable approach. However, it should be noted that the results presented in Table 6.4 do not correspond to exactly the same conditions as used for comparison of transient flow and SEEP2D models.

So far, the comparisons of the flow models were based on steady-state conditions. SEEP2D model can be solved for various heads and the results of these steady-state flow models can be compared with the results of transient flow model. As in Section 6.2, a flood wave of 60 days, a net head of 5 m, a fluctuation of 1.5 m, and a homogenous upward leakage of 0.14 1/day/m of levee were selected for this purpose. The flood wave and corresponding hydraulic gradient development at the levee toe by the Laplace Transform method is shown in Fig. 6.12.



**Fig. 6.12 Flood wave in the river and hydraulic gradient development at the levee toe by Laplace transform method with leakage, 0.14 1/day/m of levee.**

The hydraulic gradient curve in Fig. 6.12 was divided into certain ranges, and corresponding head values in the river were calculated. A series of SEEP2D models were solved by using these head values, and the range of hydraulic gradients were calculated. In SEEP2D analysis, horizontal hydraulic conductivity of the medium was adjusted in order to get the target leakage quantity at the landside of the levee. The results are presented in Table 6.5.

**Table 6.5 Summary of the range of hydraulic gradient with corresponding range of hydraulic head with time duration at the levee toe by Laplace transform method and SEEP2D model with leakage,  $L=0.14$  1/day/m of levee.**

Time Range (days)	Duration (days)	Range of Hydraulic Head in the River (m)	Range of Hydraulic Gradient at the Levee Toe	
			Laplace Transform Method	SEEP2D Model
1-3	3	5.04-5.20	0.46-0.49	0.54-0.55
4-10	7	5.27-5.71	0.51-0.60	0.56-0.61
11-19	9	5.78-6.22	0.61-0.70	0.62-0.67
20-30	21	6.26-6.46	0.71-0.75	0.67-0.69
31-40		6.46-6.26	0.75-0.71	0.69-0.67
41-49	9	6.22-5.78	0.70-0.61	0.67-0.62
50-56	7	5.71-5.27	0.60-0.51	0.61-0.56
57-60	4	5.20-4.96	0.49-0.45	0.55-0.54

As shown in Table 6.5, the results from the transient flow model and finite element analysis are still in agreement during the assumed high water event. Again, it should be noted that in SEEP2D modeling, the horizontal hydraulic conductivity value was adjusted for each hydraulic head in the river to get the target upward leakage quantity. This analysis simulates the pressure relief due to formation of sand boils during a flood, and can be useful to examine the sites with relief wells.

#### **6.4 Summary and Conclusions**

The main objective of this chapter was to show the performance of the analytical seepage model developed by Laplace transform method. The results from the analytical model were presented and compared with other seepage analysis methods. The Army Corps method outlined in Army Engineer Manual, EM 1110-2-1913 and SEEP2D finite element analysis were selected for comparison purposes.

Two sets of comparisons were conducted. In the first set, one-dimensional flow in the confined aquifer case was studied. The transient analytical model by Laplace Transform method resulted in higher exit gradients than the steady-state analysis models: the Army Corps method and SEEP2D finite element analysis. In the second set of comparisons, the Laplace transform method and SEEP2D analysis were compared for one-dimensional flow with leakage out of a confined aquifer case. The results are in agreement for different leakage quantities. The assigned upward leakage term refers to seepage flowing out through sand boils. This situation resembles relief wells and causes decreases in head development beneath the levee compared to the no leakage case.

Transient head development was also simulated by the steady-state models. The Army Corps method and SEEP2D model were analyzed for certain increments of head values and the results were compared with the transient flow model. This type of analysis can also be useful to predict the occurrence of sand boils and the performance of the sites where relief wells have been installed during a possible high water event.

The predictability of the models can only be measured and the results presented in this chapter can only be generalized with field measurements. Besides, even though a simple cross-section is compared, the comparisons do not reflect identical conditions due to the fact that each method was developed under its own assumptions. With this performance analysis, the main objective of this chapter was satisfied.

This chapter also investigated the question of whether or not transient effects are critical in the development of hydraulic gradients. The performance analysis presented in this chapter clearly shows that the transient flow models developed by Laplace transform method give reasonable results compared with the commonly used steady-state seepage analysis applications. Therefore, the transient flow models are worthwhile to consider



during an underseepage study of levees and prediction of sand boil formations at the landside of the levee.

## 6.5 List of Symbols

$b$  = thickness of pervious layer (L)

$c$  = a variable to define  $x_3$  ( $L^{-1}$ )

$h_0$  = hydraulic head beneath top stratum landside toe of the levee (L)

$H$  = total head loss (L)

$h_x$  = head beneath top stratum at distance  $x$  from landside toe of the levee (L)

$i_c$  = critical hydraulic gradient (dimensionless)

$i_x$  = hydraulic gradient beneath top stratum at landside of the levee (dimensionless)

$k_b$  = vertical hydraulic conductivity of top stratum ( $LT^{-2}$ )

$k_f$  = horizontal hydraulic conductivity of pervious layer ( $LT^{-2}$ )

$K_x$  = horizontal hydraulic conductivity of pervious layer ( $LT^{-2}$ )

$K_y$  = vertical hydraulic conductivity of pervious layer ( $LT^{-2}$ )

$L$  = leakage ( $T^{-1}L^{-1}$ )

$L$  = length dimension (L)

$L_2$  = base width of levee (L)

$L_3$  = landside extent of top stratum measured from landside levee toe (L)

$S$  = aquifer storativity (dimensionless)

$x_1$  = effective length of riverside blanket (L)

$x_3$  = distance from landside levee toe to effective seepage exit (L)

$z_b$  = thickness of landside top stratum

## **CHAPTER 7      EVALUATION OF CUMULATIVE EFFECTS**

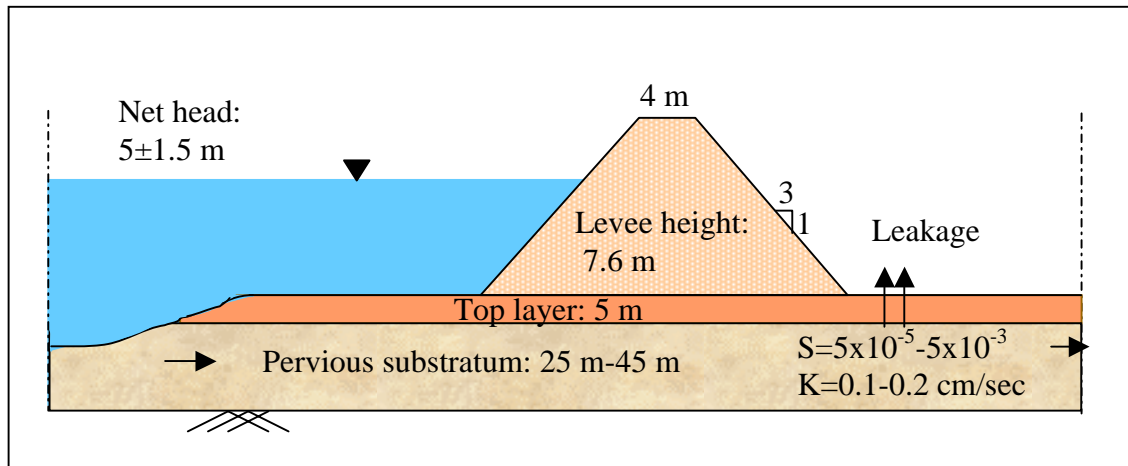
### **7.1      Introduction**

The objective of this chapter was to use the transient flow models and steady-state seepage analysis methods to evaluate possible cumulative effects caused by repetitive flood events.

In the case of piping problems under levees, the pore size may increase with time as fine soil particles are washed away due to underseepage. The increased pore size may enable the migration of larger sized soil particles. If the unobservable process proceeds and sufficient soil is transported, an internal channel may develop. A sand boil at the location where the seepage exits is an indication that an internal channel has formed, even though the channel is of small size. After a sand boil has formed, fine soil is usually discharged with the flowing water. This continued discharge of fine material might suggest the eroded internal channel is migrating from the landside of the levee toward the riverside. As an internal channel develops, enlarges, and lengthens due to cumulative effects, several parameters that are important in seepage analysis are expected to change. The thickness of pervious layer, soil porosity, soil hydraulic conductivity, and saturation degree are some of those parameters. Out of these parameters, soil porosity and degree of saturation directly effects the hydraulic conductivity of the soil layer.

In this research hydraulic conductivity of the soil medium was assumed as the most important parameter in the evaluation of possible cumulative effects due to underseepage. Therefore, a range of hydraulic conductivity values for the soil medium was assumed and then exit hydraulic gradients were evaluated for corresponding hydraulic conductivity values.

In Chapter 3, a transient analytical model was developed by the Laplace transform method. The main soil property in this model is aquifer diffusivity value, which is transmissivity over storativity ratio ( $T/S$ ). The model can be run for a range of  $T/S$  ratios to examine the effect of changes in hydraulic conductivity of the soil medium. Typical Mississippi Valley aquifer parameters were considered and a range of aquifer diffusivity values ( $T/S$ ) were selected for analysis purposes. The thickness of sandy alluvium under Mississippi River levees changes from 25 m to 45 m. The hydraulic conductivity of sandy alluvium is in the range of 0.1-0.2 cm/sec (Turnbull and Mansur 1961). Typical storativity values for confined aquifers are  $5 \times 10^{-3}$ ,  $5 \times 10^{-4}$ ,  $5 \times 10^{-5}$  (Freeze and Cherry, 1979). In the 1993 floods, the net change in river level elevation of the middle Mississippi River levees was recorded as 4.8 to 6.7 m (Mansur *et al.* 2000). A net head of 5 m and a fluctuation of 1.5 m were selected in the analysis. The typical levee section with selected aquifer parameters and hydraulic head is presented in Fig. 7.1.



**Fig. 7.1 A typical levee section with selected parameters (not in scale).**

The range of typical aquifer diffusivities for cumulative analysis purpose is shown in Table 7.1.

**Table 7.1 Selected aquifer diffusivities used in cumulative effect analysis.**

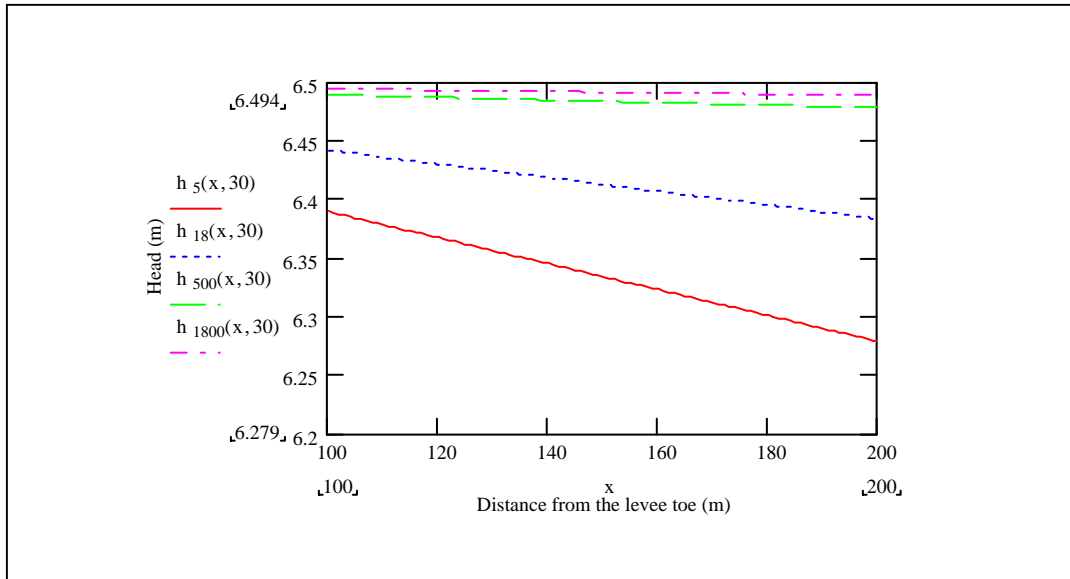
Aquifer diffusivity, T/S ratio	Hydraulic conductivity, K (cm/sec)	Thickness of aquifer (m)	Transmissivity, T (m <sup>2</sup> /sec)	Storativity (dimensionless)
5	0.1	25	0.025	$5 \times 10^{-3}$
18	0.2	45	0.090	$5 \times 10^{-3}$
500	0.1	25	0.025	$5 \times 10^{-5}$
1800	0.2	45	0.090	$5 \times 10^{-5}$

Two sets of analyses were conducted to evaluate possible cumulative effects of piping under levees. The first set of analyses included the following methods: transient analytical model by Laplace transform method, the Army Corps method, and SEEP2D finite element model. The second set of analyses was applied when there was leakage out of a confined aquifer, which simulates the loss of water by upward seepage and discharge through sand boils. For this situation, the transient flow model by Laplace transform method and SEEP2D finite element analysis were studied.

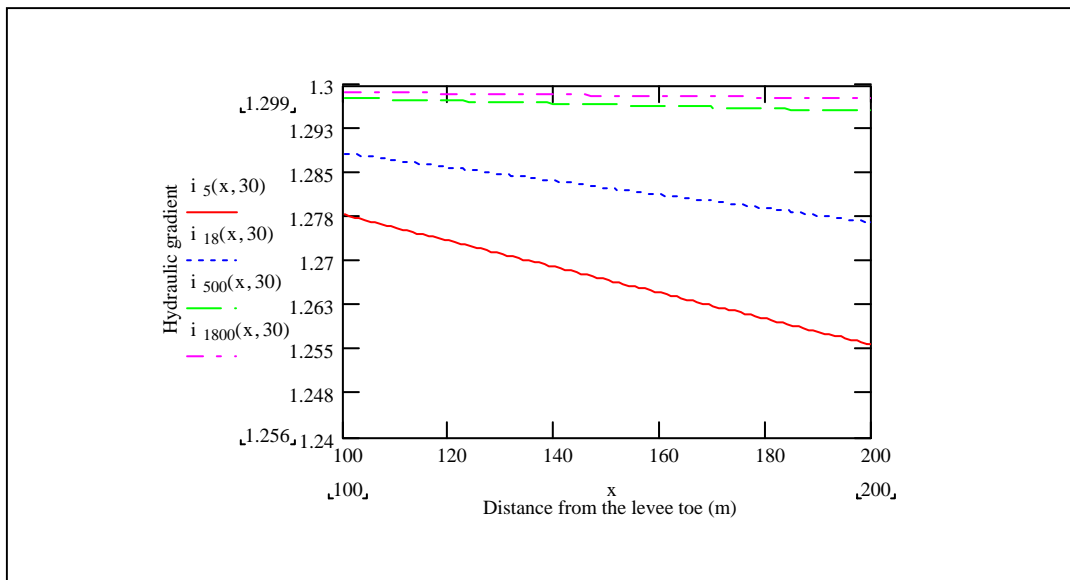
## **7.2 Cumulative Analysis for Underseepage in a Confined Aquifer**

The transient flow model applying the Laplace transform method was solved for various aquifer diffusivity values selected in Table 7.1. Hydraulic head development beneath the landside of the levee when the river head makes its peak is shown in Fig. 7.2. Hydraulic gradient development is shown in Fig. 7.3.

As aquifer diffusivity increases higher hydraulic heads and hydraulic gradients are observed on the landside of the levee (Figures 7.2 and 7.3). The results of hydraulic head and gradient development are tabulated in Table 7.2.



**Fig. 7.2 Hydraulic head development at  $t=30$  days by transient flow model for aquifer diffusivities ( $T/S$ ) of 5, 18, 500, and 1800.**



**Fig. 7.3 Hydraulic gradient development at  $t=30$  days by transient flow model for aquifer diffusivities ( $T/S$ ) of 5, 18, 500, and 1800.**

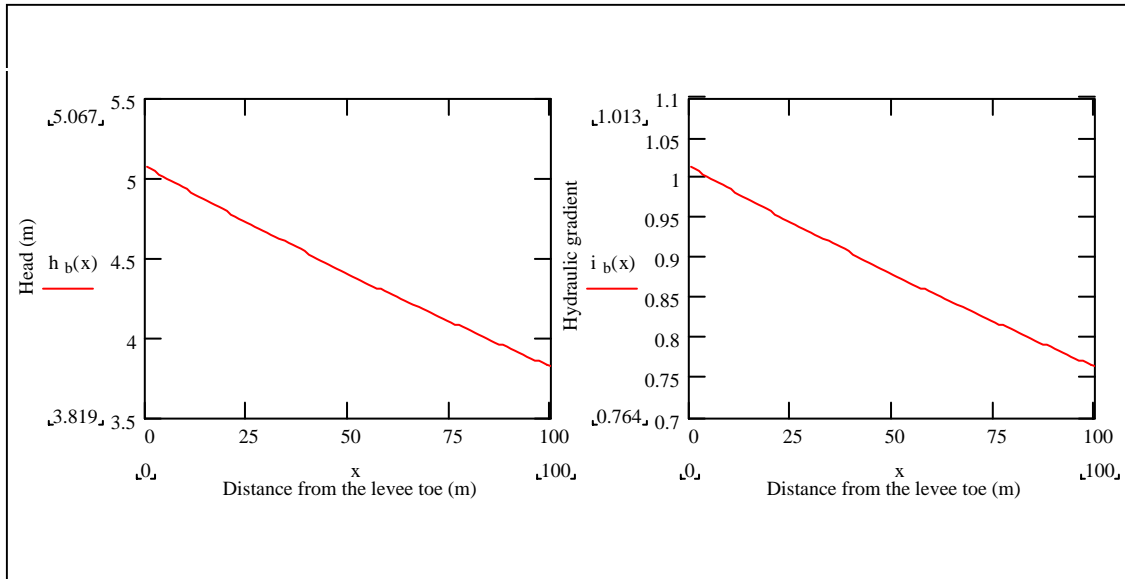
**Table 7.2 Hydraulic head beneath the landside of the levee and gradient through the top layer of a confined aquifer by transient flow model for various aquifer diffusivities.**

Aquifer diffusivity (T/S)	$h_{\text{levee toe}}$ (m)	$h_{100 \text{ m}}$ (m)	$i_{\text{levee toe}}$	$i_{100 \text{ m}}$
5 ( $T=0.025 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-3}$ )	6.389	6.279	1.278	1.256
18 ( $T=0.090 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-3}$ )	6.442	6.383	1.288	1.277
500 ( $T=0.025 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-5}$ )	6.489	6.478	1.298	1.296
1800 ( $T=0.090 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-5}$ )	6.494	6.488	1.299	1.298

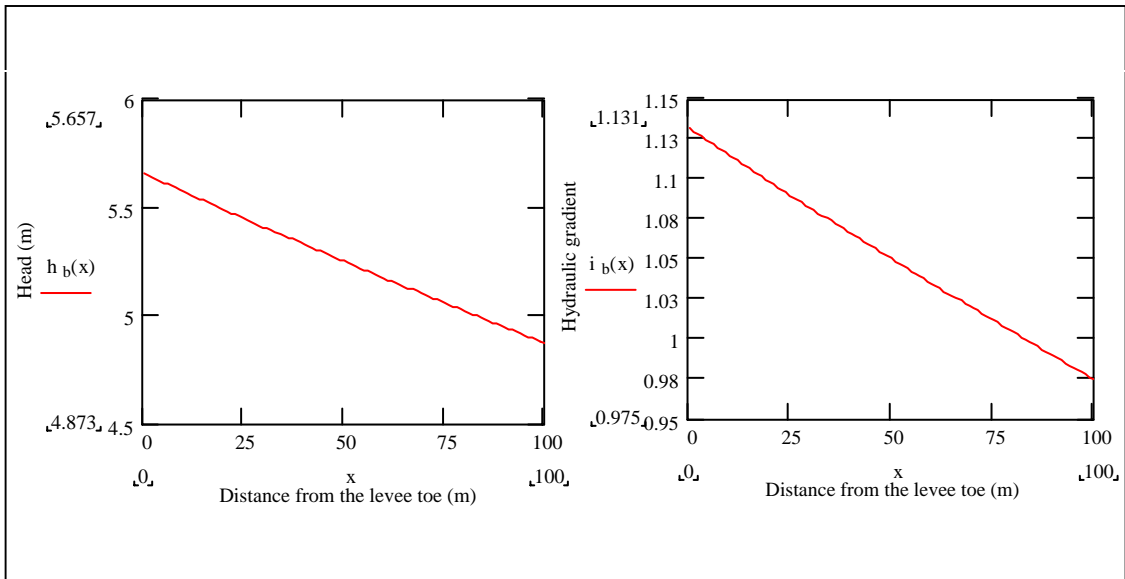
As shown in Table 7.2, the transient flow model by the Laplace transform solution results in slight increases in hydraulic head beneath the landside of the levee and the gradient through the top layer as hydraulic diffusivity of the pervious medium increases.

The Army Corps method as outlined in Engineer Manual, EM 1110-2-1913 was detailed in the sixth chapter. The formulation of the solution considers horizontal hydraulic conductivity and the depth of the pervious medium. Therefore, only aquifer transmissivity (T) of the pervious medium was increased for analysis purpose. The peak hydraulic head of 6.5 m was considered at the river. Figure 7.4 and 7.5 show hydraulic head and gradients at the landside of the levee when the aquifer transmissivities are  $0.025 \text{ m}^2/\text{sec}$  and  $0.090 \text{ m}^2/\text{sec}$ , respectively.

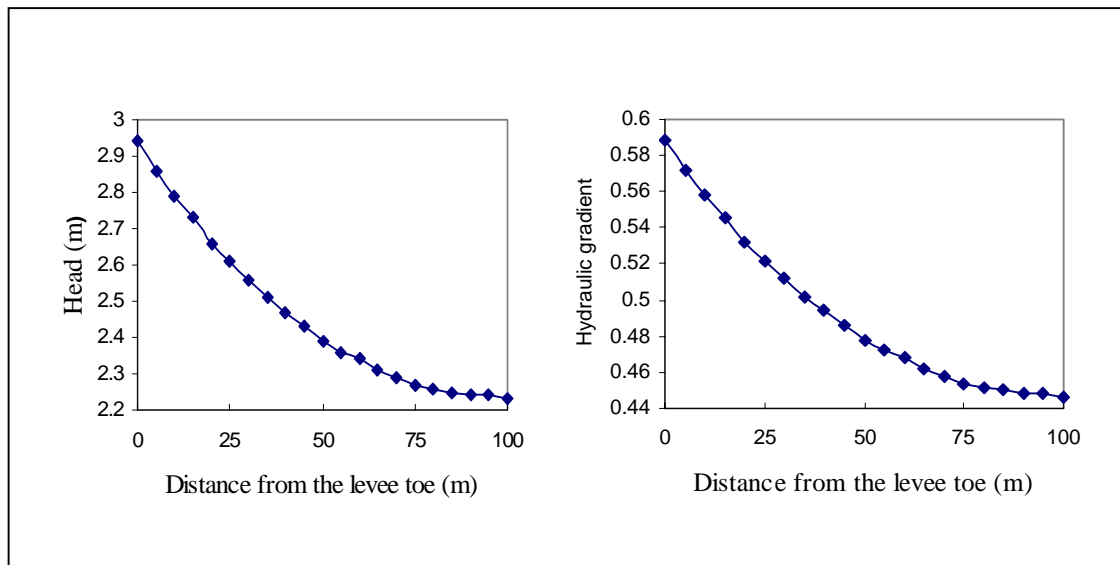
The same parameters used in the Army Corps method were also used for SEEP2D modeling. Figures 7.6 and 7.7 show the results when the aquifer transmissivities are  $0.025 \text{ m}^2/\text{sec}$  and  $0.090 \text{ m}^2/\text{sec}$ , respectively, by SEEP2D finite element analysis.



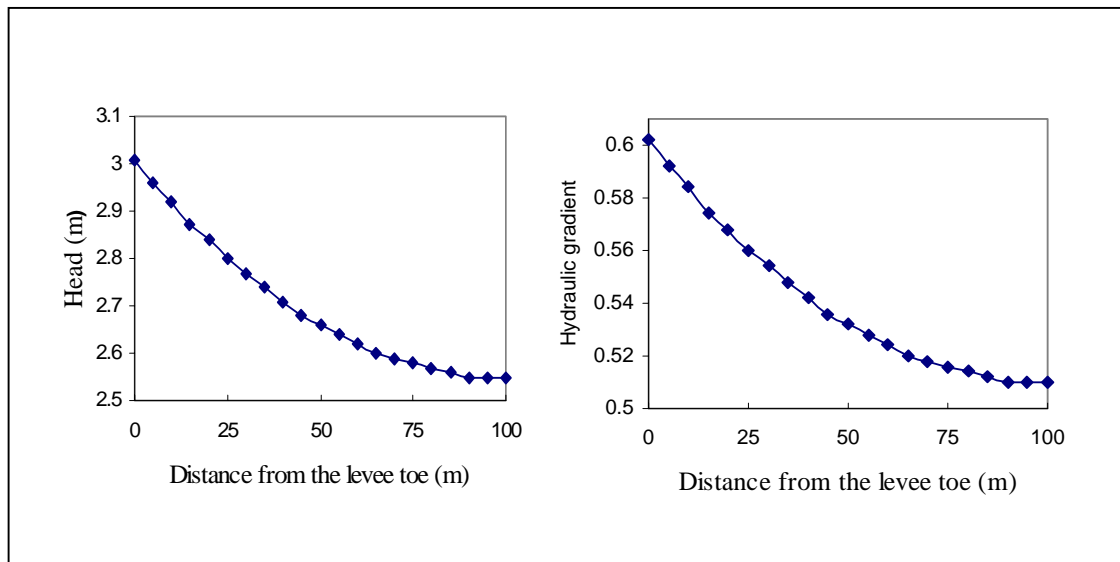
**Fig. 7.4 Hydraulic head beneath the landside of the levee and gradient development through the top layer by the USACE method for aquifer transmissivity (T) of 0.025 m<sup>2</sup>/sec.**



**Fig. 7.5 Hydraulic head beneath the landside of the levee and gradient development through the top layer by the USACE method for aquifer transmissivity (T) of 0.090 m<sup>2</sup>/sec.**



**Fig. 7.6 Hydraulic head and gradient development beneath the landside levee by SEEP2D modeling for aquifer transmissivity (T) of 0.025 m<sup>2</sup>/sec.**



**Fig. 7.7 Hydraulic head and gradient development beneath the landside levee by SEEP2D modeling for aquifer transmissivity (T) of 0.090 m<sup>2</sup>/sec.**



The changes in hydraulic gradients due to the changes in aquifer transmissivities by three of the analysis methods are summarized in Table 7.3.

**Table 7.3 Increases in hydraulic gradients (%) through the top layer on the landside of the levee by the transient flow model, the Army Corps method and SEEP2D modeling for different aquifer transmissivities.**

Methods	Aquifer transmissivity, $T$ ( $m^2/sec$ )	$i_{\text{levee toe}}$	Increase (%)	$i_{100\text{ m}}$	Increase (%)
Transient flow model ( $S=5 \times 10^{-3}$ )	0.025	1.278		1.256	
	0.090	1.288	0.78	1.277	1.67
Transient flow model ( $S=5 \times 10^{-5}$ )	0.025	1.298		1.296	
	0.090	1.299	0.08	1.298	0.15
Army Corps method	0.025	1.013		0.764	
	0.090	1.131	11.65	0.975	27.62
SEEP2D model	0.025	0.588		0.446	
	0.090	0.602	2.38	0.510	14.35

As discussed in Chapter 6, the transient flow model using the Laplace transform solution and the Army Corps method result in more conservative hydraulic gradients than SEEP2D finite element analysis (Table 7.3). This table also shows that the Laplace transform solution gives only minor changes in the exit hydraulic gradient as hydraulic diffusivity of the pervious medium changes. The Army Corps method is the most sensitive solution to the changes in transmissivity of the pervious medium.

The Laplace transform solution assumes flow over an infinite horizontal distance in the medium. Therefore, increases in aquifer transmissivity affect the head development very slightly in this assumed infinite soil medium within the first 100 m of landside levee. The Army Corps method assumes there is an upward flow on the landside of the levee. In

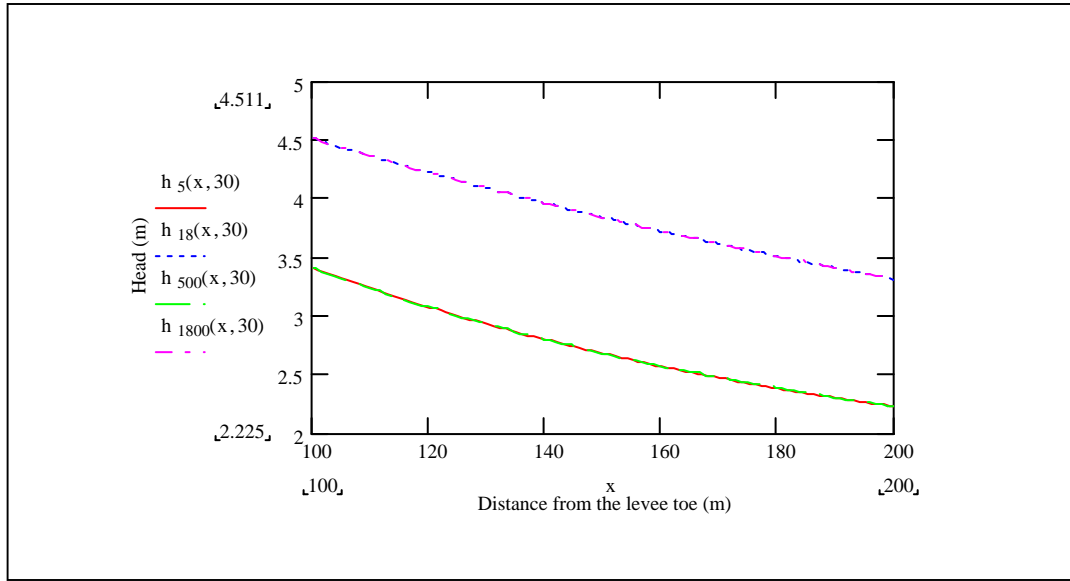
SEEP2D analysis, a confined aquifer was modeled, however, the program still allowed upward leakage concentrated at the levee toe and through the top layer on the landside of the levee. Probably, due to this upward flow in the Army Corps method and SEEP2D model, hydraulic conductivity of the medium affects the exit gradients in both models.

A change in hydraulic conductivity has an affect on exit hydraulic gradients. However, exit hydraulic gradients at a location distant from the landside of the levee were affected more than those closer to the levee.

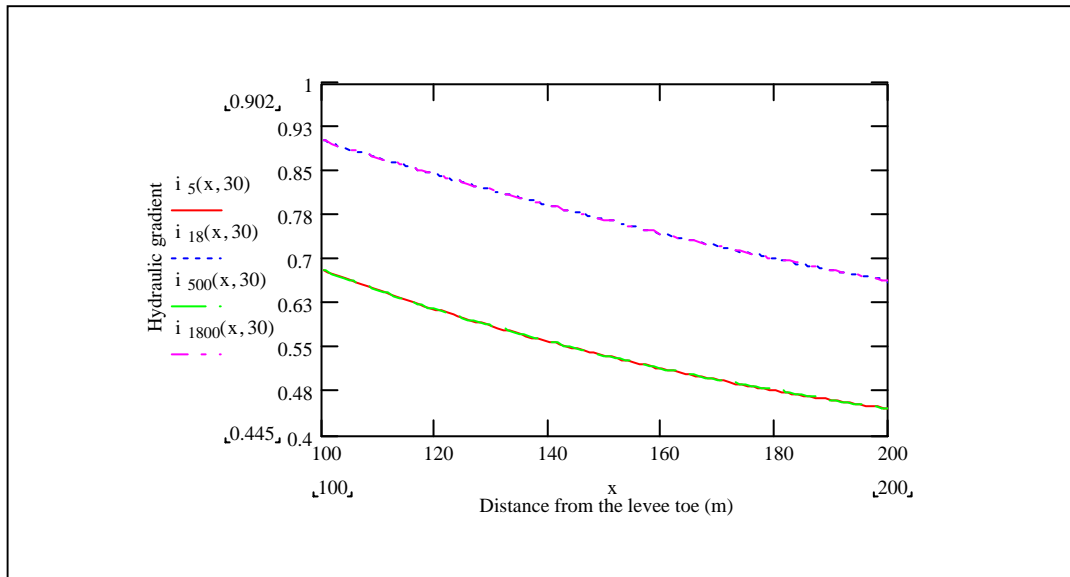
### **7.3 Cumulative Analysis for Underseepage with Leakage Out of a Confined Aquifer**

The transient flow model utilizing the Laplace transform solution and SEEP2D finite element analysis are capable of analyzing hydraulic head developments when there is an upward seepage emerging at the landside of the levee. Two separate SEEP2D models were constructed using aquifer transmissivities of  $0.025 \text{ m}^2/\text{sec}$  and  $0.090 \text{ m}^2/\text{sec}$ , respectively. The model with an aquifer transmissivity of  $0.025 \text{ m}^2/\text{sec}$  resulted in an average leakage of 0.20 1/day per meter of levee, and the model with an aquifer transmissivity of  $0.090 \text{ m}^2/\text{sec}$  resulted in an average leakage of 0.36 1/day per meter of levee. Therefore, two transient flow models were run with each leakage quantity for cumulative analysis and also for comparison purposes with SEEP2D finite element modeling. The first model of transient flow analysis used aquifer diffusivities as set in Table 7.1 and an upward leakage of 0.20 1/day/m of levee. With these parameters, hydraulic head development beneath the landside of the levee when the river head makes its peak is shown in Fig. 7.8. Hydraulic gradient development for this case is also shown in Fig. 7.9. It is important to note that hydraulic head and gradient development for

aquifer diffusivities (T/S) of 5 and 500, and 18 and 1800 almost identical (Fig. 7.8 and 7.9).



**Fig. 7.8 Hydraulic head development beneath the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.20 1/day/m of levee.**

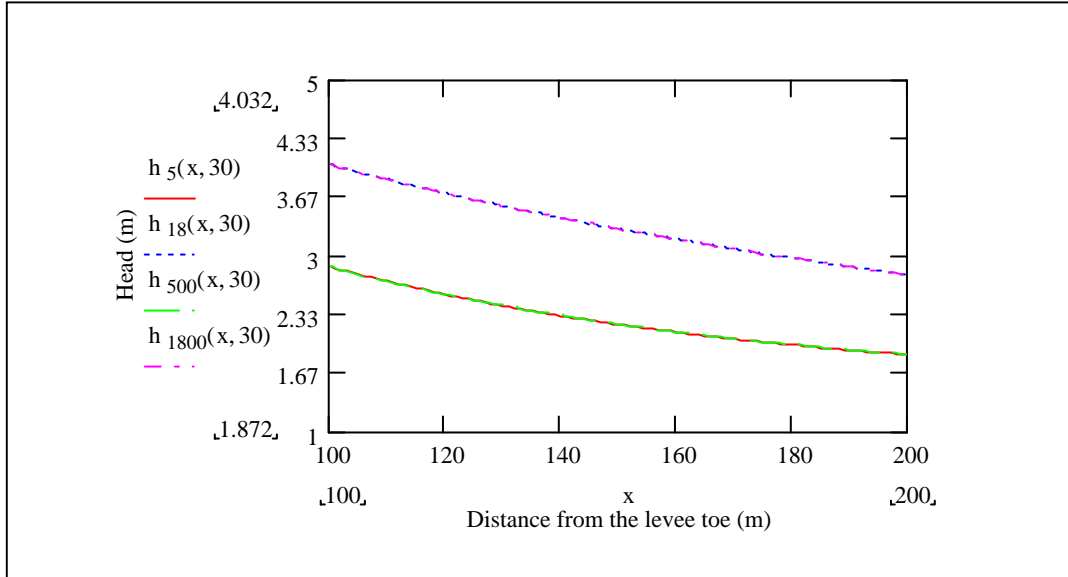


**Fig. 7.9 Hydraulic gradient development through the top layer on the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.20 1/day/m of levee.**

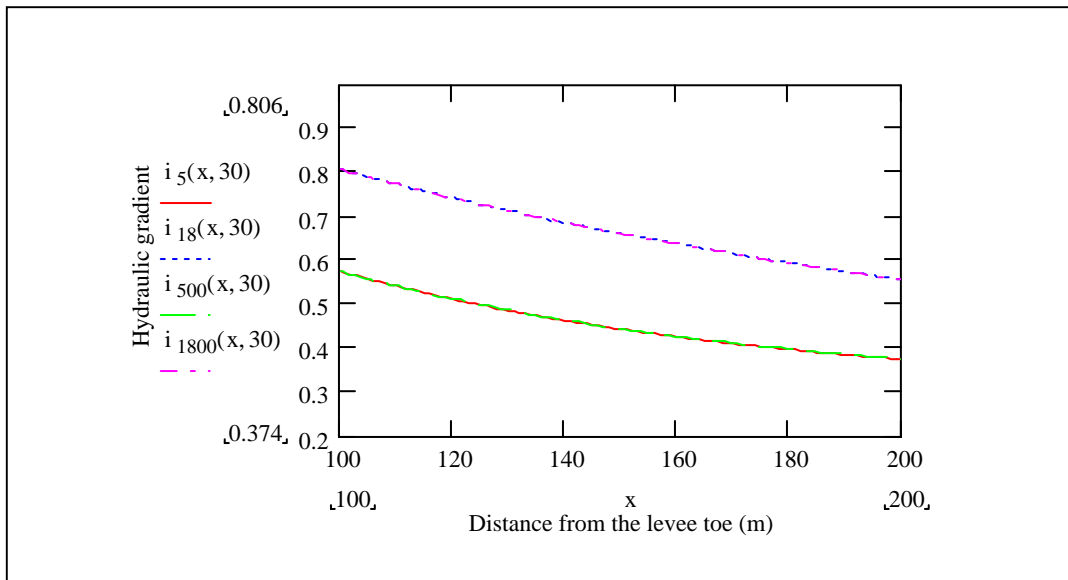
The second model of transient flow analysis also used the same aquifer diffusivities, as set in Table 7.1 and a leakage of 0.36 1/day/m of levee. With these parameters, hydraulic head development beneath the landside of the levee when the river head makes its peak is shown in Fig. 7.10, and hydraulic gradient development is shown in Fig. 7.11. Again, the hydraulic head and gradient development for aquifer diffusivities (T/S) of 5 and 500, and 18 and 1800 almost identical (Fig. 7.10 and 7.11). The results of the transient flow models as shown in Figures 7.8 through 7.11 are also tabulated in Table 7.4.

Figures 7.8 through 7.11 and Table 7.4 show that aquifer transmissivity, T, plays a more important role than does the aquifer diffusivity, T/S, in the transient flow model developed by the Laplace transform method. When the transmissivity was kept constant, the transient flow model resulted in almost identical hydraulic heads beneath the landside of the levee regardless of changes in storativity of the medium. In addition, the results indicated a considerable increase in hydraulic head and gradient development through the top layer at the landside of the levee as transmissivity of the medium increases when there is leakage out of the aquifer.

The same analysis was also studied by using SEEP2D finite element modeling. Two models were constructed. One has an aquifer depth of 25 m with a hydraulic conductivity of 0.1 cm/sec, and the other one has an aquifer depth of 45 m with a hydraulic conductivity of 0.2 cm/sec. In both models, an exit face was defined at the landside of the levee to allow upward seepage. Figures 7.12 and 7.13 show hydraulic head beneath the landside of the levee and gradient development through the top layer for aquifer transmissivities of 0.025 m<sup>2</sup>/sec and 0.090 m<sup>2</sup>/sec, respectively.



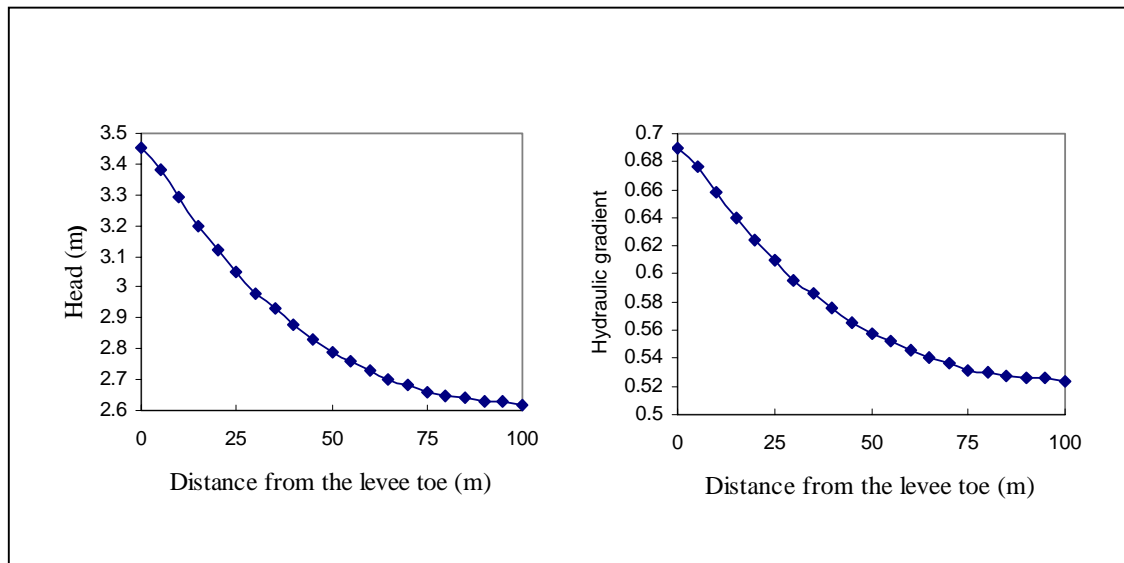
**Fig. 7.10 Hydraulic head development beneath the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.36 1/day/m of levee.**



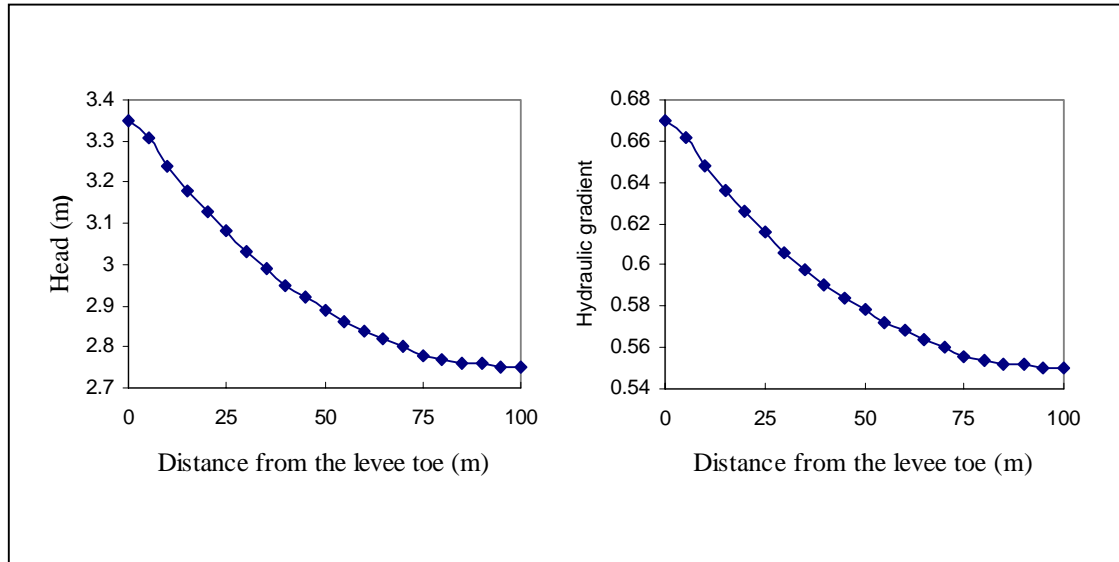
**Fig. 7.11 Hydraulic gradient development through the top layer on the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.36 1/day/m of levee.**

**Table 7.4 Hydraulic head beneath the landside of the levee and gradient through the top layer by transient flow model for various aquifer diffusivities when there is a leakage out of a confined aquifer.**

Aquifer diffusivity (T/S)	Leakage (1/day/m of levee)	$h_{\text{levee toe}}$ (m)	$h_{100 \text{ m}}$ (m)	$i_{\text{levee toe}}$	$i_{100 \text{ m}}$
5 ( $T=0.025 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-3}$ )	0.20	3.408	2.225	0.682	0.445
18 ( $T=0.090 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-3}$ )		4.510	3.312	0.902	0.662
500 ( $T=0.025 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-5}$ )		3.410	2.229	0.682	0.446
1800 ( $T=0.090 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-5}$ )		4.511	3.313	0.902	0.663
5 ( $T=0.025 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-3}$ )	0.36	2.872	1.872	0.574	0.374
18 ( $T=0.090 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-3}$ )		4.031	2.781	0.806	0.556
500 ( $T=0.025 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-5}$ )		2.875	1.878	0.575	0.376
1800 ( $T=0.090 \text{ m}^2/\text{sec}$ , $S=5 \times 10^{-5}$ )		4.032	2.782	0.806	0.556



**Fig. 7.12 Hydraulic head and gradient development beneath the landside of the levee by SEEP2D modeling for aquifer transmissivity (T) of  $0.025 \text{ m}^2/\text{sec}$  with a leakage of  $0.2 \text{ 1/day/m}$  of levee.**



**Fig. 7.13 Hydraulic head and gradient development beneath the landside of the levee by SEEP2D modeling for aquifer transmissivity (T) of  $0.090 \text{ m}^2/\text{sec}$  with a leakage of  $0.36 \text{ 1/day/m}$  of levee.**

The increases in hydraulic gradients developed through the top layer on the landside of the levee by the changes in aquifer transmissivities by transient flow model and SEEP2D analysis are summarized in Table 7.5. The transient flow model solved by the Laplace transform method shows that hydraulic gradients through the top layer on the landside of the levee significantly increase as transmissivity of the medium increases when there is seepage emerging at the landside of the levee. SEEP2D finite element analysis does not show this trend. The main reason that the software fails to do this is that the models were constructed in such a way that upward seepage cannot be kept constant while the transmissivity of the layer changes. Therefore, the results of SEEP2D analysis cannot be generalized. One common trend is that the changes in hydraulic conductivity effect exit hydraulic gradients at a location distant from the landside of the levee more than those closer to the levee. The same trend was also observed when there was no seepage allowed on the landside of the levee as discussed in the previous section.

**Table 7.5 Increases in hydraulic gradients (%) through the top layer on the landside of the levee by the transient flow model and SEEP2D analysis for different aquifer transmissivities.**

Methods	Aquifer transmissivity $T \text{ (m}^2\text{/sec)}$	Leakage (1/day/m of levee)	$i_{\text{levee toe}}$	Increase (%)	$i_{100 \text{ m}}$	Increase (%)
Transient flow model	0.025 $T/S = 5, 500$	0.20	0.682		0.445	
	0.090 $T/S = 8, 1800$	0.20	0.902	32.3	0.663	49.0
Transient flow model	0.025 $T/S = 5, 500$	0.36	0.575		0.375	
	0.090 $T/S = 8, 1800$	0.36	0.806	40.2	0.556	48.3
SEEP2D model	0.025	0.20	0.690		0.524	
SEEP2D model	0.090	0.36	0.670	-3.0	0.550	5.0

Table 7.5 also shows reasonable agreement of the exit gradients by both transient flow model and SEEP2D analysis for the same aquifer transmissivity and leakage quantities.

Further cumulative analysis can be conducted by assuming incremental changes in hydraulic conductivity of the medium. For this purpose, an incremental increase of 0.01 cm/sec was assumed in a 25-m and 45-m depth of aquifers after each flood. An upward leakage of 0.2 1/day/m of levee was assumed. Table 7.6 presents the changes in hydraulic gradient at the levee toe and 100-m farther at the landside of the levee with the Laplace transform solution.



**Table 7.6 Increases in hydraulic gradients (%) through the top layer on the landside of the levee by the transient flow model due to an incremental increase in hydraulic conductivity of the medium.**

K (m/sec)	Aquifer thickness = 25 m				Aquifer thickness = 45 m			
	i <sub>levee toe</sub>	Increase (%)	i <sub>100 m</sub>	Increase (%)	i <sub>levee toe</sub>	Increase (%)	i <sub>100 m</sub>	Increase (%)
0.0010	0.682		0.445		0.788		0.538	
0.0011	0.699	2.5	0.459	3.1	0.804	2.0	0.554	3.0
0.0012	0.715	2.3	0.472	2.8	0.819	1.9	0.570	2.9
0.0013	0.730	2.1	0.484	2.5	0.833	1.7	0.584	2.5
0.0014	0.743	1.8	0.496	2.5	0.845	1.4	0.597	2.2
0.0015	0.756	1.7	0.507	2.2	0.857	1.4	0.610	2.2
0.0016	0.767	1.5	0.518	2.2	0.867	1.2	0.621	1.8
0.0017	0.778	1.4	0.528	1.9	0.877	1.2	0.633	1.9
0.0018	0.788	1.3	0.538	1.9	0.886	1.0	0.643	1.6
0.0019	0.797	1.1	0.547	1.7	0.894	0.9	0.653	1.6
0.0020	0.806	1.1	0.556	1.6	0.902	0.9	0.662	1.4

Table 7.6 shows that the hydraulic gradient at the levee toe increases from 0.682 to 0.806 after possible cumulative effects of assumed repetitive flood events causing an increase in hydraulic conductivity of the medium. This table also supports the trend that the changes in hydraulic conductivity effect exit hydraulic gradients at a location distant from the landside of the levee more than those closer to the levee. Table 7.6 also shows that the 25-m depth aquifer is more sensitive to possible cumulative effects than the 45-m depth aquifer suggesting the thickness of the aquifer is important factor in predicting cumulative effects.

## 7.4 Summary and Conclusions

This chapter discusses the possible cumulative effects due to repetitive underseepage processes. In Chapter 3, a transient flow model was developed by the Laplace transform method. In Chapter 4, the model was revised when there was an upward seepage out of the aquifer. In this chapter, cumulative effects were evaluated with and without an upward seepage at the landside of the levee.

For cumulative analysis of underseepage in a confined aquifer, the transient flow model by the Laplace transform method, the Army Corps method and SEEP2D finite element analysis were used. The results indicated that the transient flow model did not show any considerable increase in exit gradients as the aquifer transmissivity increases. The Army Corps method and SEEP2D analysis showed considerable increases in exit gradients in response to increases in aquifer transmissivities.

For cumulative analysis of underseepage with leakage out of a confined aquifer, the transient flow model by the Laplace transform method and SEEP2D finite element analysis were used. The results indicated that the transient flow model showed significant increases in exit hydraulic gradients in response to increases in aquifer diffusivities during seepage emerging at the landside of the levee. This result implies that the regions where sand boils were observed may experience more dramatic underseepage problems in the next flood event due to cumulative effects. A similar trend cannot be associated with the results of SEEP2D finite element analysis. However, the increases in exit gradients by SEEP2D analysis are not expected to be as significant as the increases that resulted from the transient flow model when there is an upward seepage at the landside of the levee. The exit gradients are also in agreement when comparing the transient flow model and SEEP2D finite element analysis.

An interesting common trend in cumulative analysis is that the cumulative effects seem to result in higher exit gradients farther from the landside of the levee than at the toe of the levee. This trend leads us to expect that critical underseepage problems may develop farther from the landside of the levee due to cumulative effects of underseepage. As presented in Section 2.3.1, sand boils were reported up to 2.4-km landside from the Mississippi River levees. Cumulative effects may be among the reasons for the occurrence of sand boil formations at surprisingly far distances from the levees. However, this argument is applicable to the assumption of a homogenous increase in hydraulic conductivity of the pervious medium along the landside of the levee.

The objective of this chapter was satisfied with the analysis presented. This chapter also examined one of the main questions of this research: how transient flow analysis in conjunction with current underseepage analysis tools responds to possible cumulative effects problem. As noted in the literature survey, there is no published study on cumulative effects of underseepage problems associated with sand boils. The approach followed in this chapter helps to evaluate possible cumulative effects by the tools developed and used in this research. Long term site monitoring is needed in the field to confirm the application and the results of the tools used in this chapter.

## **CHAPTER 8      CONCLUDING REMARKS**

The phenomena of seepage under hydraulic structures and formation of sand boils is quite complicated by a variety of factors including complex geological features and other discontinuities due to man made works, natural processes and organic agencies. As discussed in Chapter 2, qualitative and quantitative models and a number of tools exist to successfully perform underseepage analysis of levees. However, in literature, transient conditions associated with sand boil problems have not been studied in detail. This study investigated transient effects of seepage flow under levees associated with sand boil formation. The results of this research allow practicing engineers:

- (1) to develop hydraulic gradient profile through the landside of a levee for rising and falling river stages,
- (2) to consider possible site-specific cumulative effects due to repetitive flood, and
- (3) to be aware of a time-lag between the river head fluctuations and the formation of uplift and sand boils at the landside of a levee.

Two transient flow models were developed: one was for the transient hydraulic head development in a confined aquifer and the other was for the transient hydraulic head development with leakage out of a confined aquifer. The second model simulated the occurrence of loss of water by upward seepage and discharge through sand boils. Two different solutions were presented for each model, and the exact solution, Laplace transform solution, was studied in detail. With the development of transient flow models the first and the second objectives of this research presented in Chapter1 were satisfied.

The developed flow models are practical tools to examine transient cases. In general, the models performed well. The transient flow model in confined aquifers is more conservative than the Army Corps method and SEEP2D finite element program.

The transient flow model with homogenous upward leakage out of confined aquifers is in good agreement with the SEEP2D finite element model.

Two-dimensional transient flow nets were also constructed based on analytical solutions to the governing equations, and they provide useful information to investigate head development beneath the landside of a levee. In addition, the solutions provide an analytical benchmark against which to compare numerical contributions to formulations of the flow nets. The third objective of this research was satisfied with this task.

Cumulative effects due to repetitive flood events were discussed. The response of transient flow models and the current underseepage analysis tools make it possible to evaluate some of the cumulative effects that may be associated with sand boil enlargement and piping from a series of floods. The transient flow model with leakage out of a confined aquifer showed significant increases in exit hydraulic gradients in response to cumulative effects.

This dissertation explored the following two questions that were set in Chapter 1: (1) Is transient flow analysis due to river head fluctuations critical in the development of exit hydraulic gradients and the subsequent sand boil formation? and (2) If sand boils develop more frequently due to cumulative effects associated with repetitive flood events, how can transient flow analysis in conjunction with current underseepage analysis tools respond to this problem?

The first question was explored in Chapter 6. This chapter also satisfied the fourth objective of this research. The transient flow analysis can provide critical information in the development of exit hydraulic gradients and subsequent sand boil formation. However, a combination of further field, laboratory, and model studies are needed to document changes in exit gradients with a series of floods. The second question was

discussed in Chapter 7. This chapter also satisfied the fifth objective of this research. The transient flow analysis with upward leakage responded significantly to possible cumulative effects of repetitive underseepage of levees. For the case of no upward leakage, the Army Corps method and SEEP2D finite element analysis are more susceptible to the changes in the aquifer transmissivities than the transient flow model.

The present models can be further investigated for case studies. Some modifications can be considered in the application of transient flow models according to the site-specific underseepage history. Some of the modifications that appear warranted are adjustment in upward leakage quantity, use of both transient flow models, with and without upward leakage, and considering a time lag in head development between the river head and landside of the levee. Analysis in the sites with relief wells would also be very useful to test transient flow model with upward leakage.

The Army Corps method for underseepage analysis of levees is the state-of-art practice. Therefore, the Army Corps method can be taken as a base for comparison with the transient flow models. Currently, the Laplace transform solution without upward leakage case provides more conservative results than the Army Corps method. An error range can be determined for the transient flow models with extensive site-specific studies.

Other than experimental and field studies, transient and cumulative effects of repetitive high water events can also be further investigated by analytical methods. Transient models can be applied to the underseepage analysis in conjunction with the migration of wetting front. The changes in soil parameters due to saturation and migration of fines can be incorporated into transient flow models in order to determine

the effects of prolonged high water. One subject that would be beneficial to study is the migration characteristics of different sized particles in natural strata under levees.

Overall, transient seepage flow analysis due to fluctuating river head conditions can be an important view point to adopt in the study of underseepage of levees associated with sand boil problems. Further analytical, field and laboratory studies are recommended to address the transient and cumulative effects of seepage under levees.

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## APPENDIX A CALCULATIONS AND GRAPHS IN CHAPTER 3 AND 4

### Calculations and Graphs in Chapter 3

#### Transient Flow Model by Laplace Transform Method

$$S := 0.005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day}$$

$$\omega := \frac{\pi}{60} \quad r := \omega \quad \theta := \frac{\pi}{2} \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \dots$$

$$+ \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$H_0 := 5 \text{ meter}$$

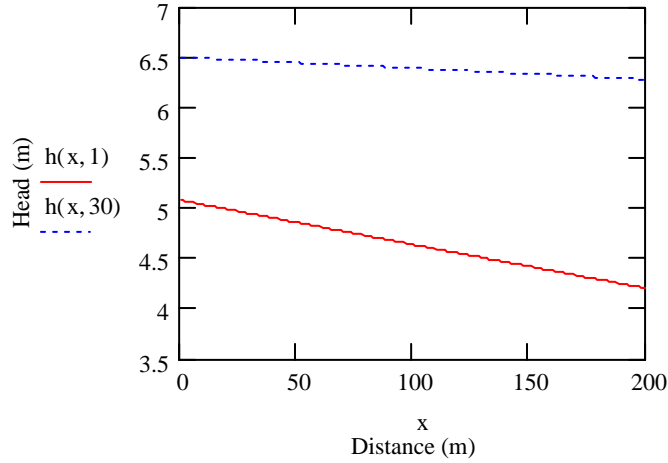
$$H_1 := 1.5 \text{ meter}$$

$$h_{im}(x, t) := \frac{1}{2} \cdot H_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot H_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \right]$$

**Figure 3.4**

$$h(x,t) := H_0 \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h_{im}(x,t)$$

$x := 0, 1..200$  m



$$h(0, 1) = 5.079$$

$$h(0, 30) = 6.5$$

$$h(100, 1) = 4.638$$

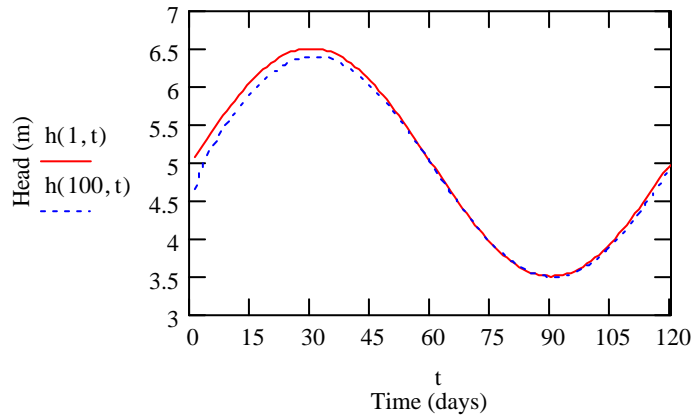
$$h(100, 30) = 6.389$$

$$h(200, 1) = 4.203$$

$$h(200, 30) = 6.279$$

**Figure 3.5**

$t := 0..120$



$$h(1, 30) = 6.499 \quad h(100, 30) = 6.389$$

**Figure 3.6**

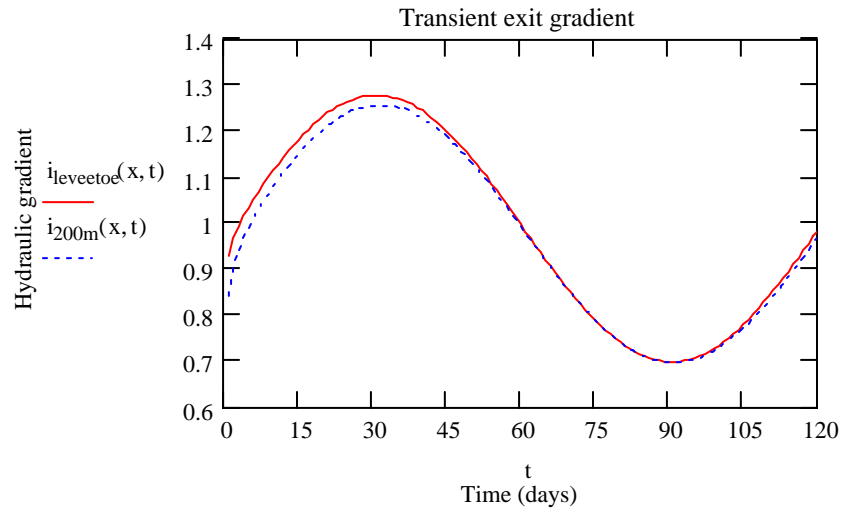
$x := 100 \quad t := 0..120$

Thickness of upper layer is assumed as 5 m

$$i_{\text{leveetoe}}(x,t) := \frac{h(100,t)}{5}$$

$$i_{200m}(x,t) := \frac{h(200,t)}{5}$$

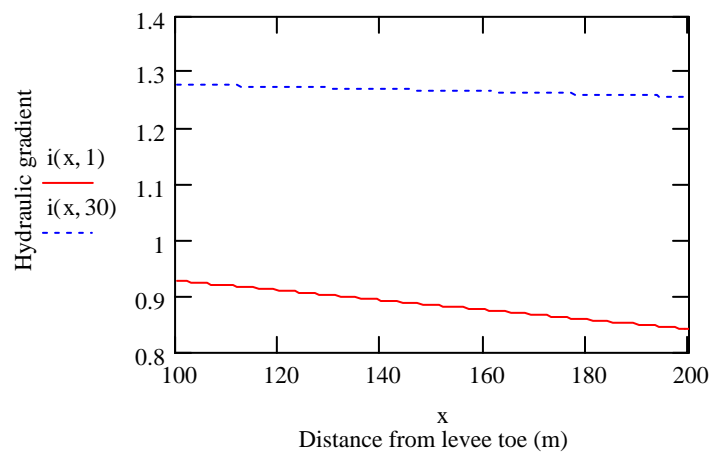




$$i_{\text{leeve toe}}(x, 30) = 1.278 \quad i_{200\text{m}}(x, 30) = 1.256$$

**Figure 3.7**

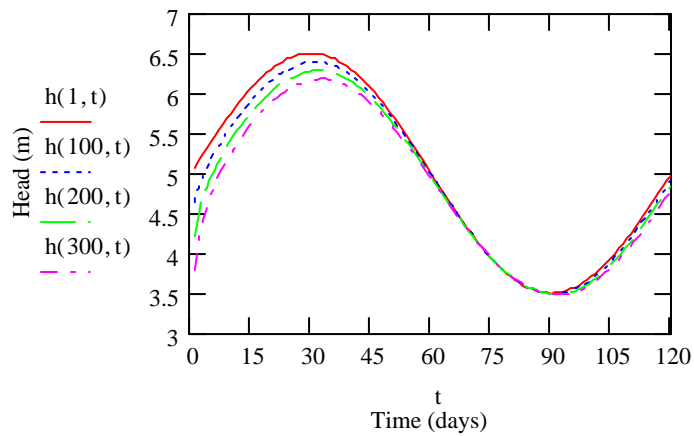
$$i(x, t) := \frac{h(x, t)}{5} \quad x := 100..200$$



$$i(200, 1) = 0.841 \quad i(200, 30) = 1.256 \quad i(100, 1) = 0.928 \quad i(100, 30) = 1.278$$

**Figure 3.12**

$$t := 0..120$$



t := 29..33      h(100,t) =      h(200,t) =      h(300,t) =

6.384	6.271	6.157
6.389	6.279	6.168
6.39	6.283	6.175
6.387	6.283	6.178
6.38	6.279	6.177

### Transient Flow Model by an Approximate Method

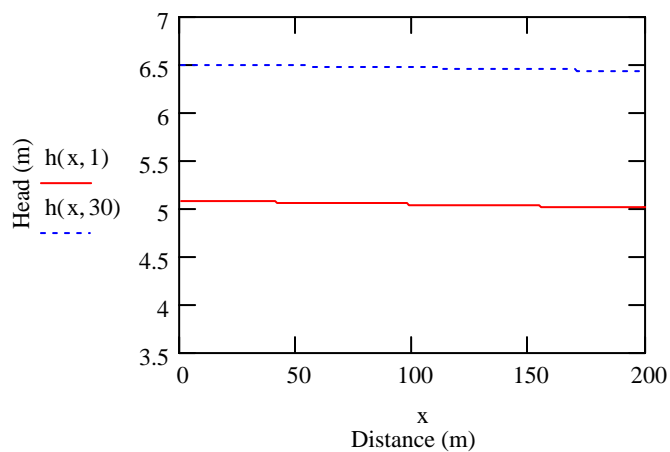
S := 0.005 dimensionless      T := 0.02586400 m<sup>2</sup>/day

$$\omega := \frac{\pi}{60} \quad p := \sqrt{\frac{\omega \cdot S}{2 \cdot T}} \quad h_0 := 5 \text{ m} \quad h_1 := 1.5 \text{ m}$$

$$h(x,t) := h_0 + h_1 \cdot e^{-p \cdot x} \cdot \sin\left(\omega \cdot t - \frac{\omega \cdot S}{2 \cdot p \cdot T} \cdot x\right)$$

**Figure 3.8**

t := 1      x := 0, 1..200 m

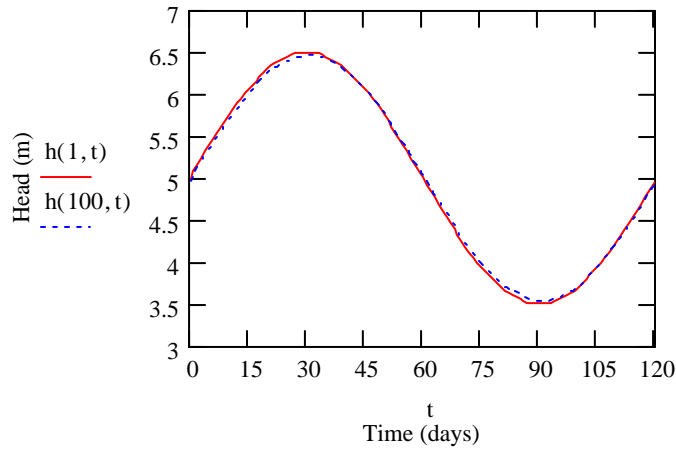


h(100, 1) = 5.041      h(100, 30) = 6.463

h(200, 1) = 5.004      h(200, 30) = 6.426

**Figure 3.9**

$t := 0, 1..120$



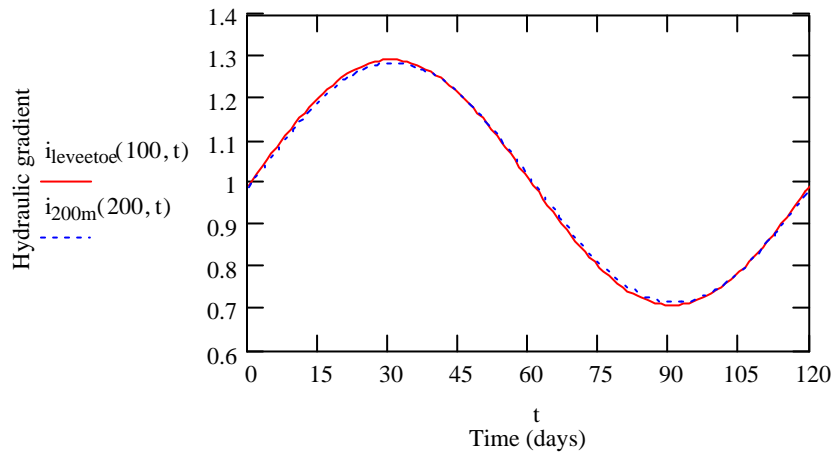
$$h(1, 30) = 6.5 \quad h(100, 30) = 6.463$$

**Figure 3.10**

$t := 0..120$  days

Thickness of upper layer is assumed as 5 m

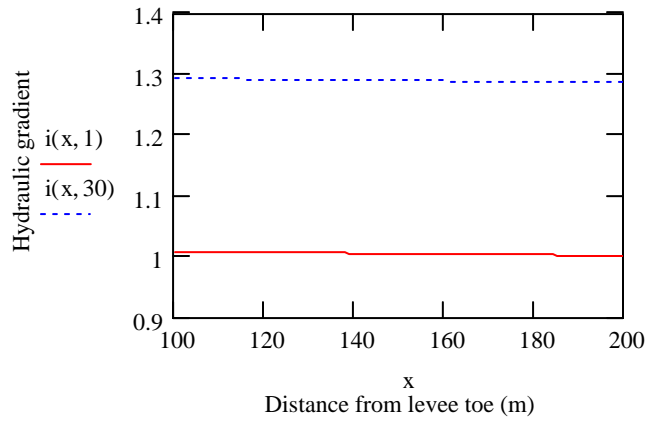
$$i_{\text{leveetoe}}(x, t) := \frac{h(100, t)}{5} \quad i_{200m}(x, t) := \frac{h(200, t)}{5}$$



$$i_{\text{leveetoe}}(100, 0) = 0.993 \quad i_{200m}(200, 90) = 0.715$$

**Figure 3.11**

$$i(x, t) := \frac{h(x, t)}{5} \quad x := 100..200$$



$$i(100, 1) = 1.008$$

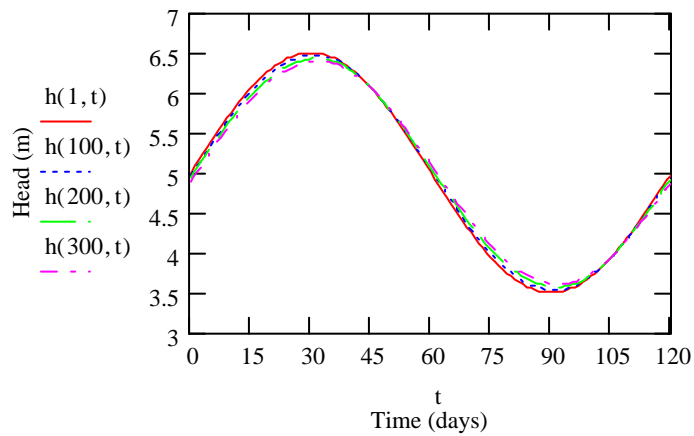
$$i(200, 1) = 1.001$$

$$i(100, 30) = 1.293$$

$$i(200, 30) = 1.285$$

**Figure 3.13**

$t := 0..120$



$t := 29..33$

$h(100, t) =$

6.459
6.463
6.463
6.459
6.451

$h(200, t) =$

6.421
6.426
6.428
6.426
6.42

$h(300, t) =$

6.382
6.389
6.393
6.393
6.388

## Calculations and Graphs in Chapter 4

### Transient Flow Model by Laplace Transform Method with Leakage Out of Confined Aquifer

$$S := 0.005 \text{ dimensionless}$$

$$T := 0.02586400 \text{ m}^2/\text{day}$$

$$L := 0.14$$

$$\omega := \frac{\pi}{60}$$

$$m := 100$$

$$\theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

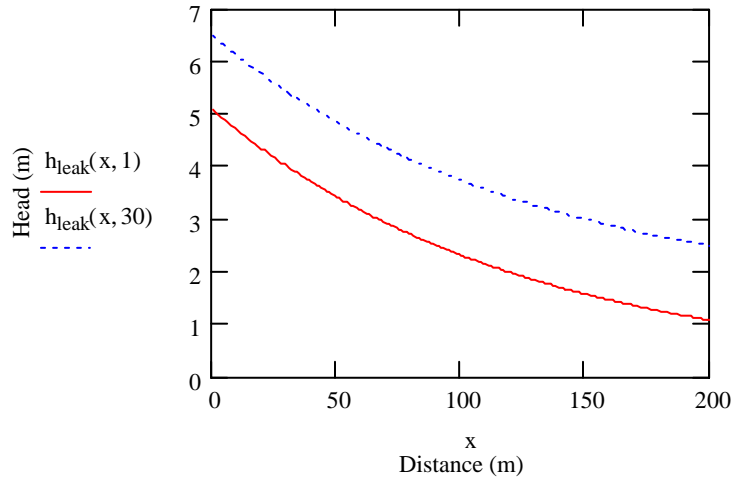
$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_{\text{leak}}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**Figure 4.4**

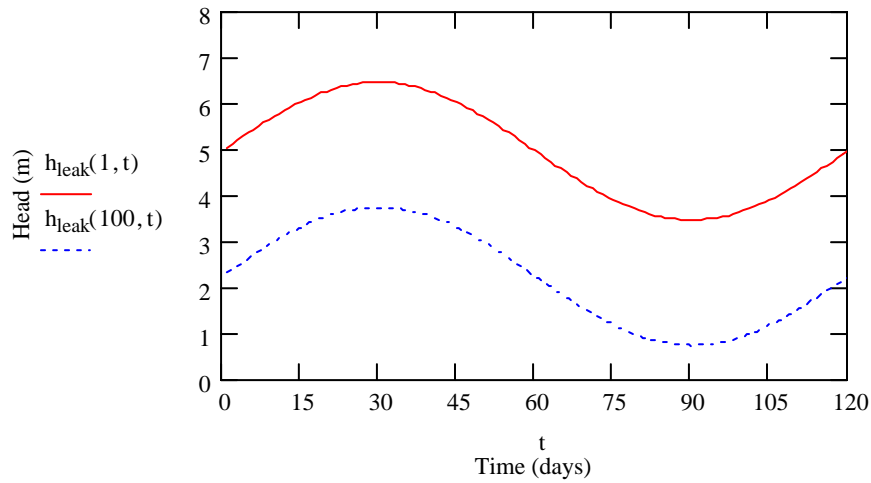
$x := 0, 1..200$  m



$$h_{\text{leak}}(100, 1) = 2.314 \quad h_{\text{leak}}(200, 1) = 1.078 \quad h_{\text{leak}}(100, 30) = 3.733 \quad h_{\text{leak}}(200, 30) = 2.496$$

**Figure 4.5**

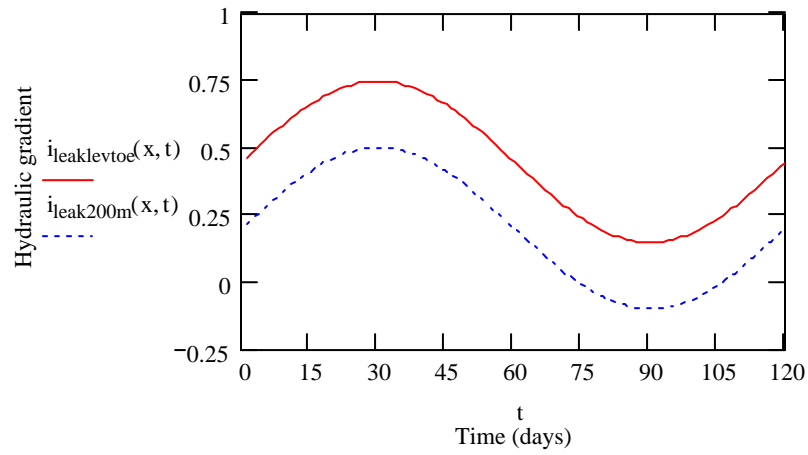
$t := 0..120$



**Figure 4.6**

$x := 100 \quad t := 0..120$

$$i_{\text{leaklevtoe}}(x, t) := \frac{h_{\text{leak}}(100, t)}{5} \quad i_{\text{leak200m}}(x, t) := \frac{h_{\text{leak}}(200, t)}{5}$$

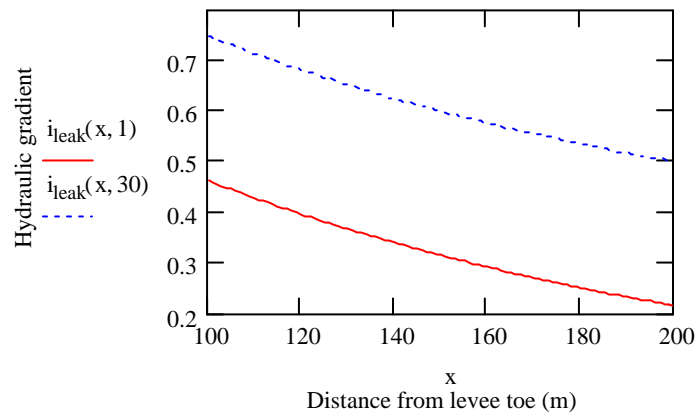


$$i_{\text{leaklevtoe}}(x, 120) = 0.447 \quad i_{\text{leak200m}}(x, 120) = 0.2$$

**Figure 4.7**

$$i_{\text{leak}}(x, t) := \frac{h_{\text{leak}}(x, t)}{5}$$

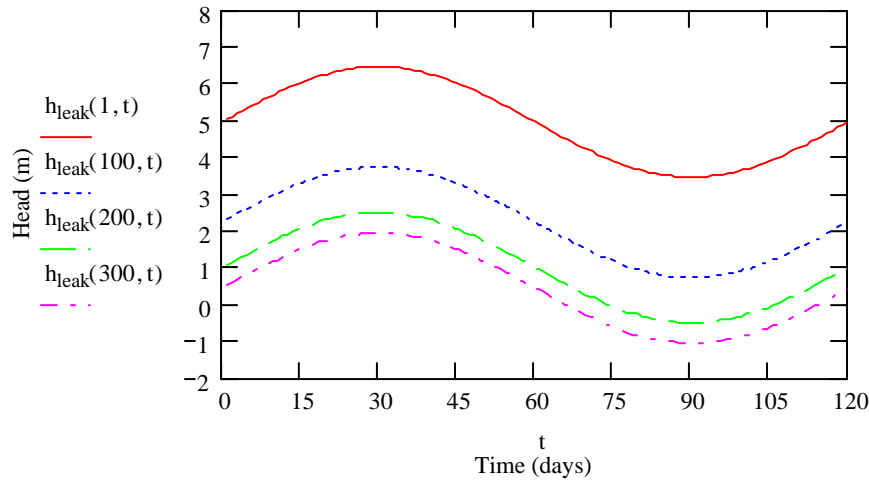
$$x := 100..200$$



$$i_{\text{leak}}(200, 1) = 0.216 \quad i_{\text{leak}}(200, 30) = 0.499 \quad i_{\text{leak}}(100, 1) = 0.463 \quad i_{\text{leak}}(100, 30) = 0.747$$

**Figure 4.14**

$$t := 0..120$$



t := 29..32

h<sub>leak</sub>(1, t) = h<sub>leak</sub>(100, t) : h<sub>leak</sub>(200, t) : h<sub>leak</sub>(300, t) :

6.458	3.731	2.494	1.939
6.46	3.733	2.496	1.941
6.458	3.731	2.494	1.939
6.452	3.725	2.487	1.933

### Calculations for Figure 4.12, L=0.28 1/day

S := 0.005 dimensionless      T := 0.025 86400m<sup>2</sup>/day      L := 0.28    ω :=  $\frac{\pi}{60}$

m := 100

$$\theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

h<sub>0</sub> := 5 meter

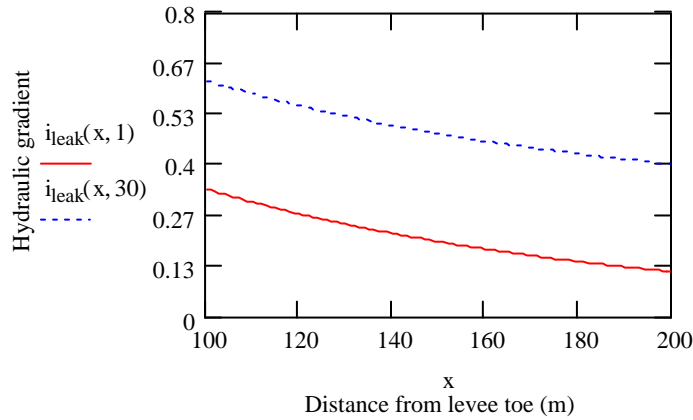
h<sub>1</sub> := 1.5 meter



$$\begin{aligned}
h_{\text{leak}}(x, t) := & \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\
& \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\
& \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\
& \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\
& + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\
& \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\
& \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\
& \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\
& + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}}\right) + \exp\left(x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}}\right) \right)
\end{aligned}$$

**Figure 4.12**

$$i_{\text{leak}}(x, t) := \frac{h_{\text{leak}}(x, t)}{5} \quad x := 100..200$$



$$i_{\text{leak}}(200, 1) = 0.118 \quad i_{\text{leak}}(200, 30) = 0.402 \quad i_{\text{leak}}(100, 1) = 0.336 \quad i_{\text{leak}}(100, 30) = 0.62$$

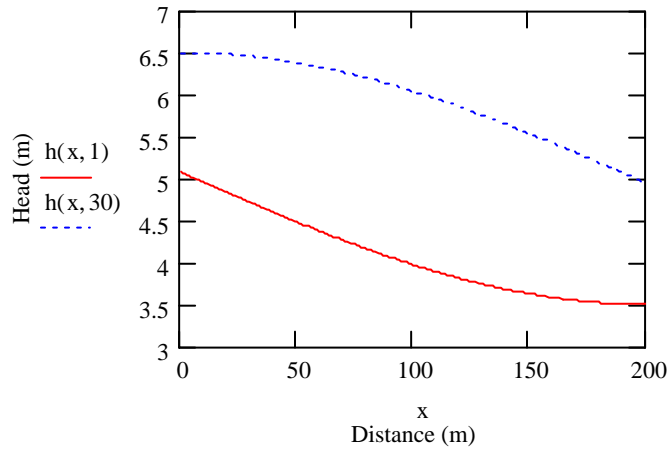
### Transient Flow Model by an Approximate Method with Leakage Out of Confined Aquifer

$$S := 0.005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day} \quad L := 0.141/\text{day} \quad \omega := \frac{\pi}{60} \quad h_0 := 5 \text{ m} \quad h_1 := 1.5 \text{ m}$$

$$p := \frac{1}{\sqrt{2}} \cdot \left[ \left[ \left( \frac{L}{T} \right)^2 + \left( \frac{S \cdot \omega}{T} \right)^2 \right]^{\frac{1}{2}} - \frac{L}{T} \right]^{\frac{1}{2}} \quad h(x,t) := h_0 + h_1 \cdot e^{-p \cdot x} \cdot \sin \left( \omega \cdot t - \frac{\omega \cdot S}{2 \cdot p \cdot T} \cdot x \right)$$

**Figure 4.8**

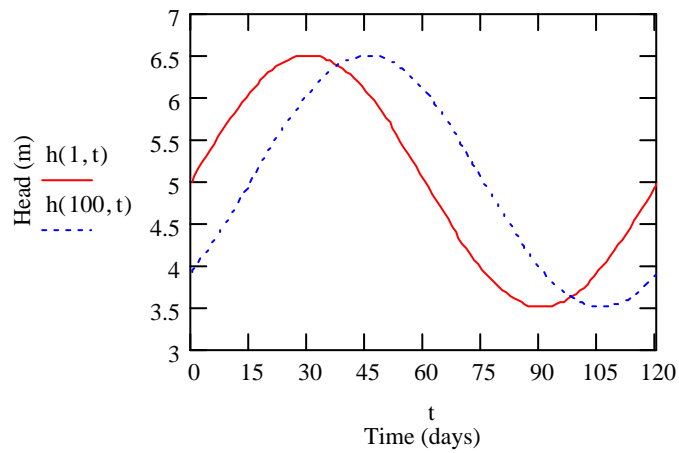
t := 1    x := 0, 1.. 200 m



$h(100, 1) = 3.975$     $h(200, 1) = 3.502$     $h(100, 30) = 6.039$     $h(200, 30) = 4.941$

**Figure 4.9**

t := 0, 1.. 120 days

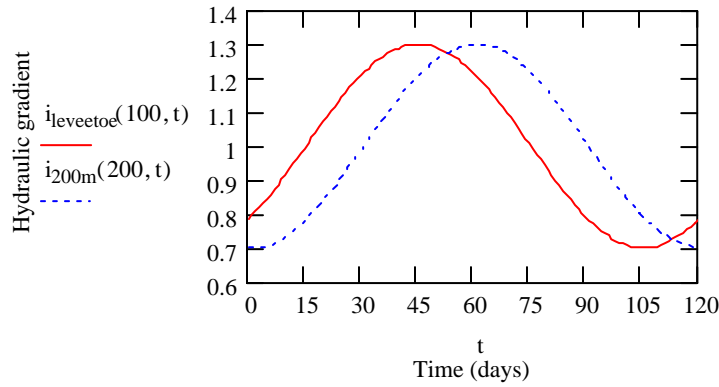


$h(100, 48) = 6.485$     $h(1, 30) = 6.5$

**Figure 4.10**

t := 0.. 120 days

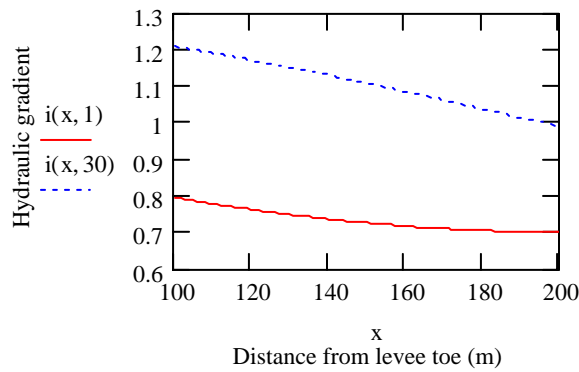
$$i_{\text{leveetoe}}(x, t) := \frac{h(100, t)}{5} \quad i_{200\text{m}}(x, t) := \frac{h(200, t)}{5}$$



$$i_{\text{levetoee}}(100, 50) = 1.291 \quad i_{200\text{m}}(200, 68) = 1.278$$

**Figure 4.11**

$$i(x, t) := \frac{h(x, t)}{5} \quad x := 100..200$$



$$i(100, 1) = 0.795 \quad i(200, 1) = 0.7 \quad i(100, 30) = 1.208 \quad i(200, 30) = 0.988$$

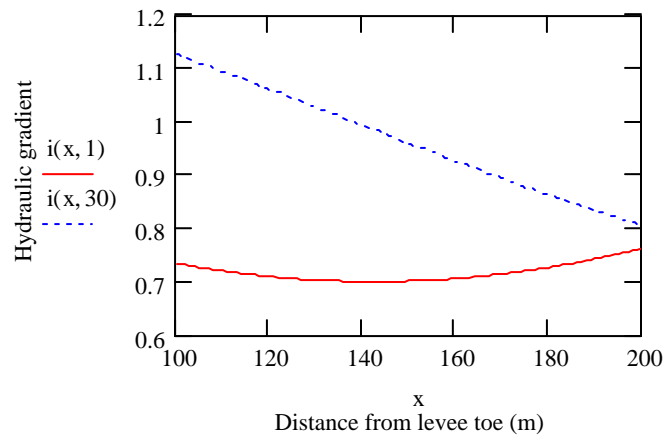
**Calculations for Figure 4.13,  $L=0.28$  1/day**

$$S := 0.005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day} \quad L := 0.28 \text{ 1/day} \quad \omega := \frac{\pi}{60} \quad h_0 := 5 \text{ m} \quad h_1 := 1.5 \text{ m}$$

$$p := \frac{1}{\sqrt{2}} \cdot \left[ \left[ \left( \frac{L}{T} \right)^2 + \left( \frac{S \cdot \omega}{T} \right)^2 \right]^{\frac{1}{2}} - \frac{L}{T} \right]^{\frac{1}{2}} \quad h(x, t) := h_0 + h_1 \cdot e^{-p \cdot x} \cdot \sin \left( \omega \cdot t - \frac{\omega \cdot S}{2 \cdot p \cdot T} \cdot x \right)$$

**Figure 4.13**

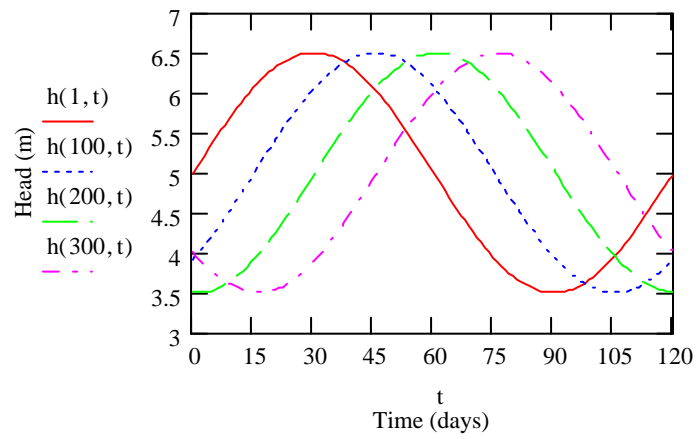
$$i(x, t) := \frac{h(x, t)}{5} \quad x := 100..200$$



$$i(100, 1) = 0.735 \quad i(200, 1) = 0.762 \quad i(100, 30) = 1.126 \quad i(200, 30) = 0.805$$

**Figure 4.15**

$t := 0..120$



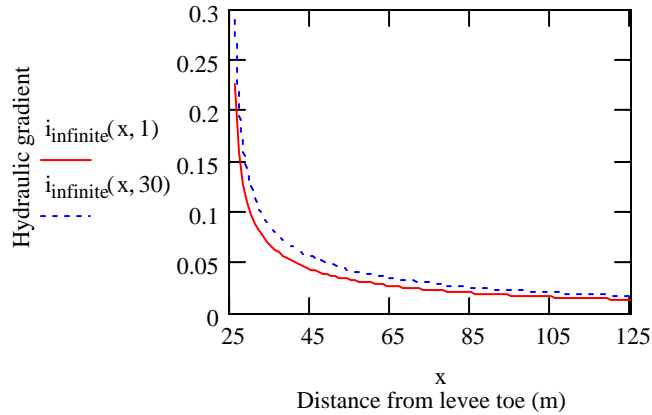
## APPENDIX B CALCULATIONS AND GRAPHS IN CHAPTER 5

$$\omega := \frac{\pi}{60} \quad h_0 := 5 \text{ m} \quad h_1 := 1.5 \text{ m} \quad b := 25 \text{ m}$$

$$h(t) := h_0 + h_1 \cdot \sin(\omega \cdot t) \quad i_{\text{infinite}}(x, t) := \frac{h(t)}{\pi \sqrt{x^2 - b^2}}$$

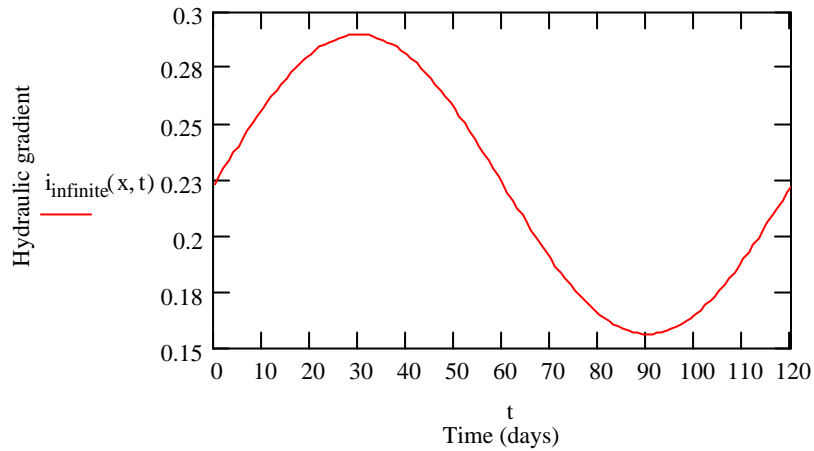
**Figure 5.3**

$x := 25..125 \text{ m}$



**Figure 5.4**

$t := 0..120 \text{ day} \quad x := 26 \text{ m}$



### Transient flow net for infinite depth aquifer:

Equipotential lines:

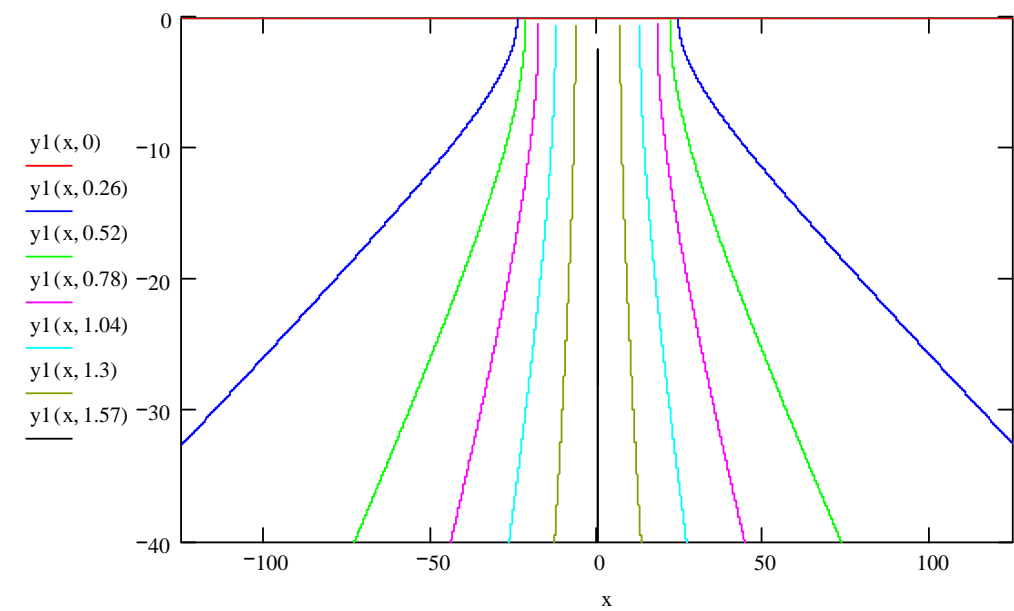
$$b := 25 \quad \omega := \frac{\pi}{60} \quad h_0 := 5 \quad h_1 := 1.5 \quad t := 10 \quad k := 86.4 \frac{\text{m}}{\text{d}}$$

$$h := h_0 + h_1 \cdot \sin(\omega \cdot t) \quad x := 125, 124.99..-125$$

$$\phi := 0,41..246 \quad \phi_1(\phi,k,h) := \frac{\pi \cdot \phi}{k \cdot h} \quad y_1(x,\phi_1) := -\sqrt{x^2 \cdot \tan(\phi_1)^2 - b^2 \cdot \sin(\phi_1)^2}$$

$$\phi_1(\phi,k,h) =$$

0
0.259
0.519
0.778
1.037
1.296
1.556



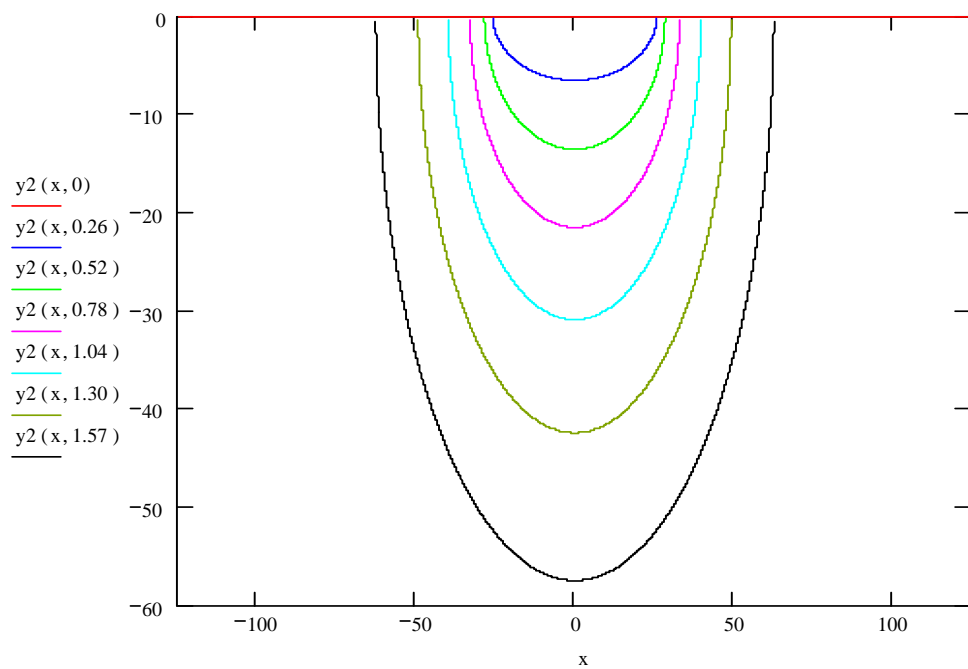
Streamlines:

$$x := 125, 124.99..-125 \quad \psi := 0,41..246 \quad \psi_1(\psi,k,h) := \frac{\pi \cdot \psi}{k \cdot h}$$

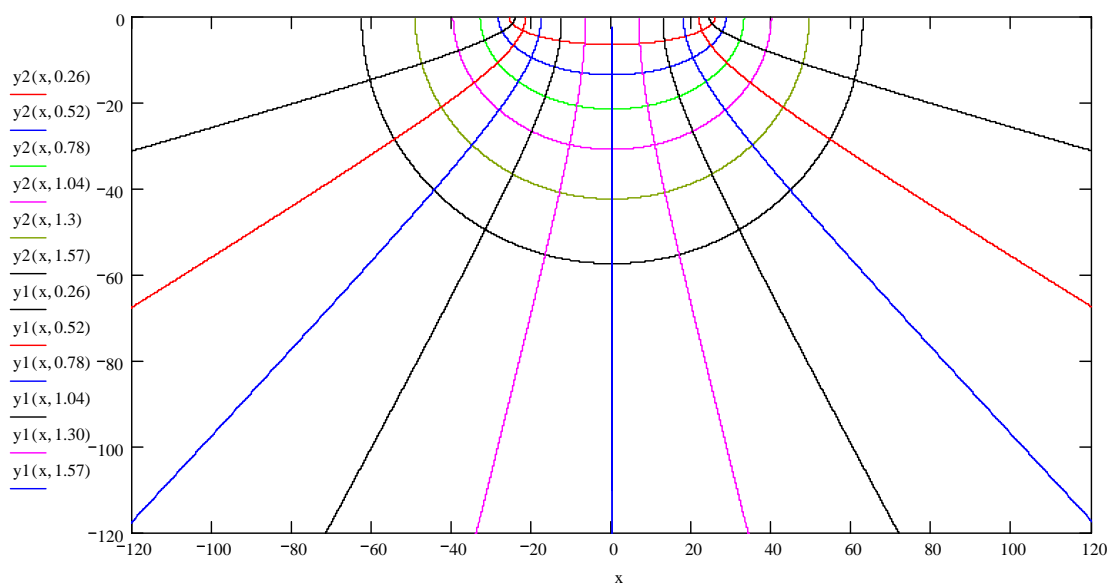
$$y_2(x,\psi_1) := -\sqrt{b^2 \cdot \sinh(\psi_1)^2 - x^2 \cdot \tanh(\psi_1)^2}$$

$$\psi_1(\psi,k,h) =$$

0
0.259
0.519
0.778
1.037
1.296
1.556



**Figure 5.5**



**Figure 5.6**

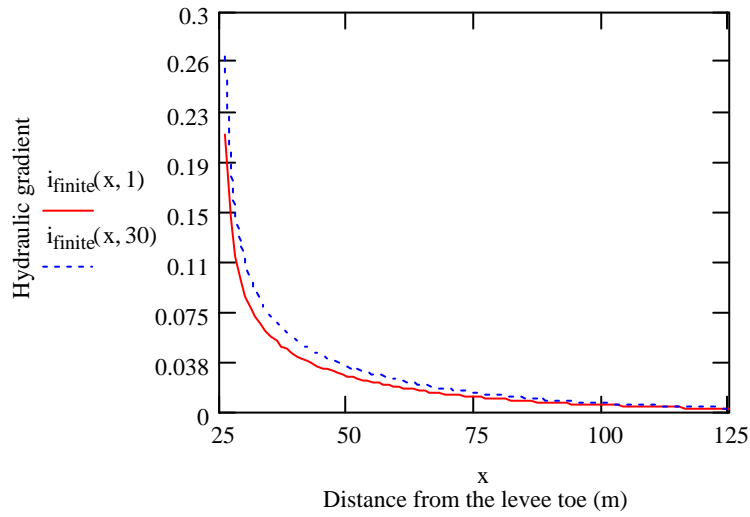
Finite depth aquifers:

$$b := 25 \quad \omega := \frac{\pi}{60} \quad h_0 := 5 \text{ m} \quad h_1 := 1.5 \text{ m} \quad T := 50 \text{ m}$$

$$z := \tanh\left(\frac{\pi \cdot b}{2 \cdot T}\right) \quad h(t) := h_0 + h_1 \cdot \sin(\omega \cdot t) \quad z^2 = 0.43 \quad K := 1.799$$

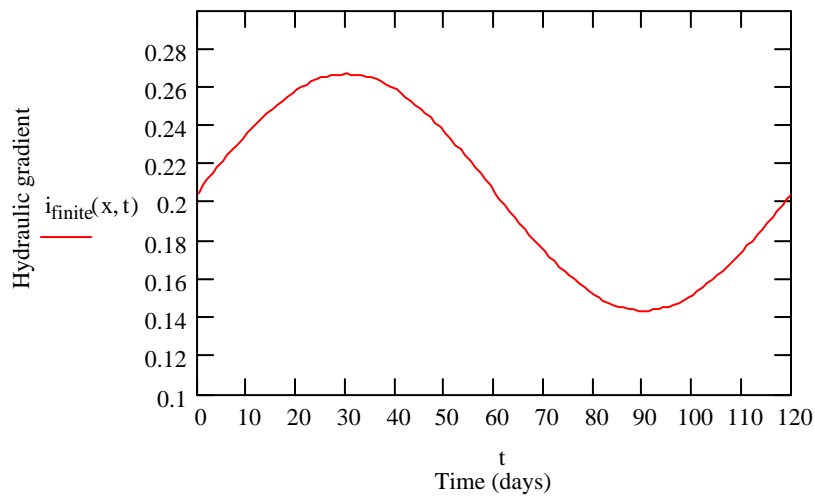
$$i_{\text{finite}}(x, t) := \frac{h(t) \cdot \pi}{4 \cdot K \cdot T} \cdot \frac{\cosh\left(\frac{\pi \cdot b}{2 \cdot T}\right)}{\sqrt{\sinh\left[\pi \cdot \frac{(b+x)}{2 \cdot T}\right] \cdot \sinh\left[\pi \cdot \frac{(x-b)}{2 \cdot T}\right]}}$$

$$x := 26..125$$



**Figure 5.7**

$$x := 26 \text{ m} \quad t := 0..120 \text{ day}$$





### Transient flow net for finite depth aquifer:

$$t := 10 \text{ } \omega := \frac{\pi}{60} \quad h_0 := 5 \quad h_1 := 1.5 \quad K := 1.799 \quad K_1 := 1.918 \quad T := 50 \quad l := 25$$

$$z := \tanh\left(\frac{\pi \cdot l}{2 \cdot T}\right) \quad h(t) := h_0 + h_1 \cdot \sin(\omega \cdot t) \quad z = 0.656 \quad z^2 = 0.43$$

$$\alpha := \frac{\pi \cdot K_1}{2 \cdot K} \quad k := 86.4$$

$$\phi := 0, 20..500 \quad \psi := 0, 100..800$$

$$\phi_1(\phi, h) := \frac{\phi}{k \cdot h(t)} \quad \psi_1(\psi, h) := \frac{\psi}{k \cdot h(t)}$$

$$X(h, \phi, \psi) := \frac{4 \cdot T}{\pi} \cdot \left[ \sum_{n=0}^{20} \frac{\cos[(2 \cdot n + 1) \pi \cdot \phi_1(\phi, h)] \cdot \cosh[(2 \cdot n + 1) \cdot \psi_1(\psi, h)]}{(2 \cdot n + 1) \cdot \sinh[(2 \cdot n + 1) \cdot \alpha]} \right]$$

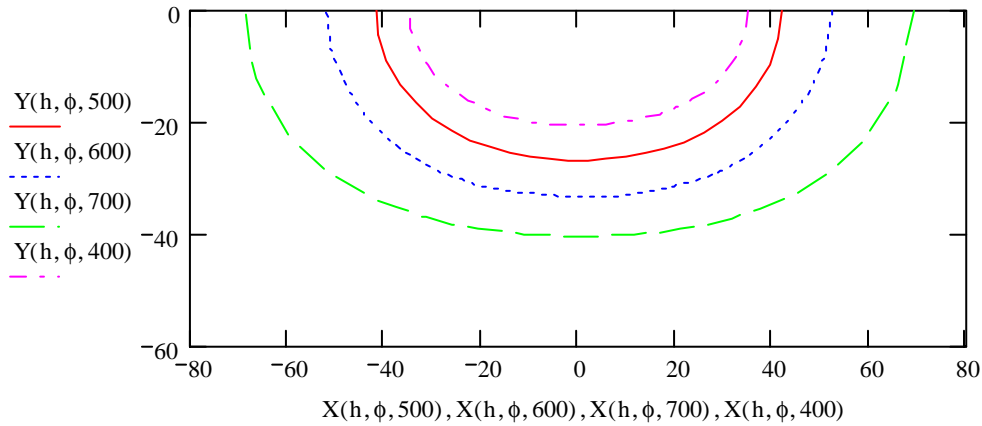
$$Y(h, \phi, \psi) := \frac{-4 \cdot T}{\pi} \cdot \left[ \sum_{n=0}^{20} \frac{\sin[(2 \cdot n + 1) \pi \cdot \phi_1(\phi, h)] \cdot \sinh[(2 \cdot n + 1) \cdot \psi_1(\psi, h)]}{(2 \cdot n + 1) \cdot \sinh[(2 \cdot n + 1) \cdot \alpha]} \right]$$

**Figure 5.8**

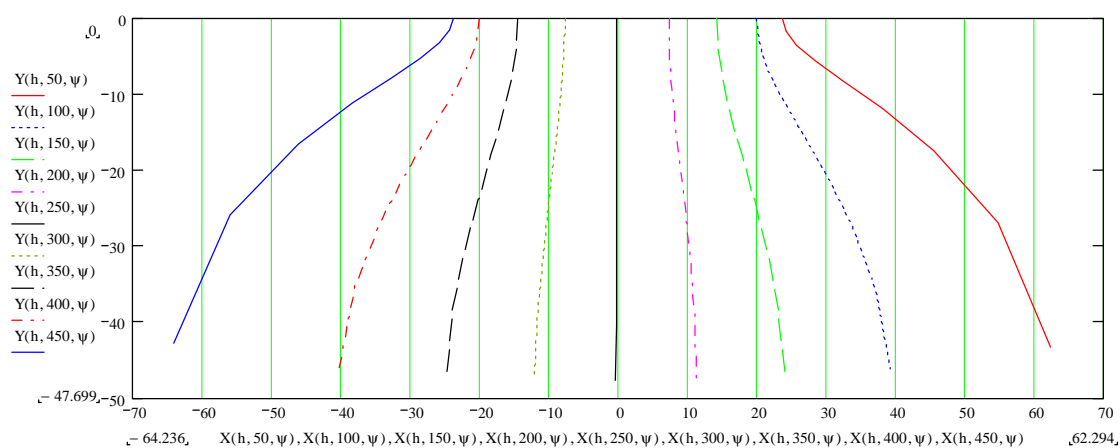
Note: Microsoft Excel was used to create the final figure.

$$t := 10 \text{ days}$$

$$\phi := 0, 20..500$$



$$\psi := 0, 100..800$$



## APPENDIX C CALCULATIONS AND GRAPHS IN CHAPTER 6

### Transient Analytical Model by Laplace Transform Method

$$S := 0.005 \text{ dimensionless}$$

$$T := 0.02586400 \text{ m}^2/\text{day}$$

$$\omega := \frac{\pi}{60} \quad r := \omega \quad \theta := \frac{\pi}{2} \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$m := 100$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \dots$$

$$+ \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$H_0 := 5 \text{ meter}$$

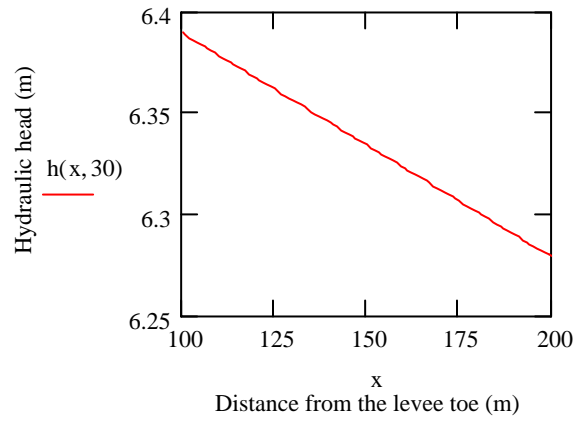
$$H_1 := 1.5 \text{ meter}$$

$$h_{im}(x, t) := \frac{1}{2} \cdot H_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot H_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \right]$$

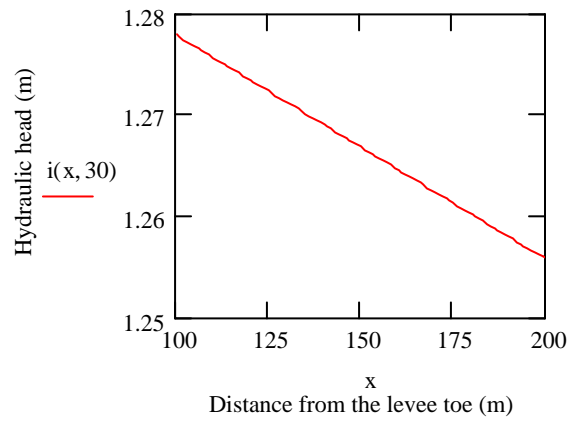
**Figure 6.5**

$$h(x, t) := H_0 \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h_{\text{im}}(x, t)$$

$x := 100..200$  m

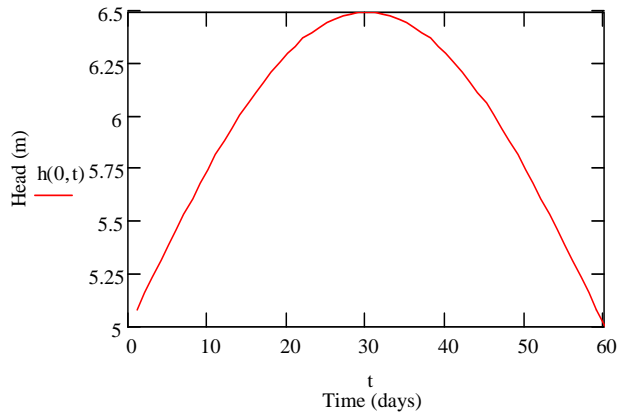


$$i(x, t) := \frac{h(x, t)}{5}$$



**Figure 6.8**

$t := 0..60$

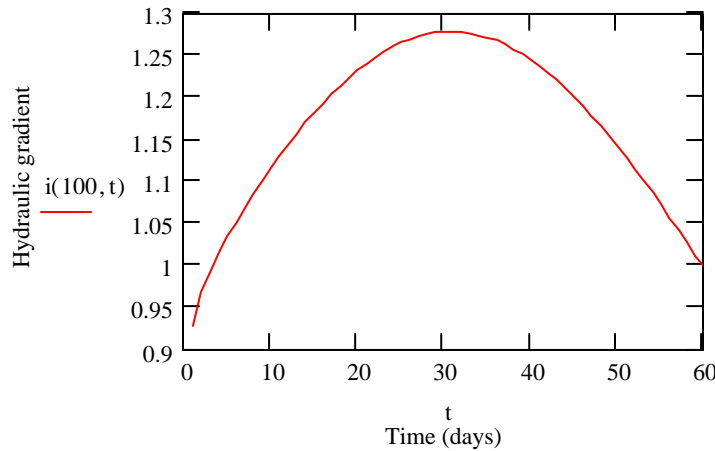


$x := 100$

Thickness of upper layer is assumed as 5 m

$t := 0..60$

$$i(x,t) := \frac{h(100,t)}{5}$$



### Calculation of Substratum Pressures by the Army Corps Method

EM 1110-2-1913: Design and Construction of Levees details the underseepage analysis. The equations contained in the manual were developed during a study reported in (U.S. Army Engineer Waterways Experiment Station TM 3-424, Appendix A) of piezometric data and seepage measurements along the Lower Mississippi River and confirmed by model studies.

Case 7, which is a semipervious top strata both riverside and landside was selected.

$H := 6.5\text{m}$  head at the riverside       $x_1 := 50\text{m}$        $L_2 := 50\text{m}$

$d := 25\text{m}$       assumed thickness of pervious aquifer

$z_b := 5\text{m}$  assumed thickness of top layer

$k_f := 0.1 \cdot 10^{-2} \frac{\text{m}}{\text{s}}$  hydraulic conductivity of pervious substratum

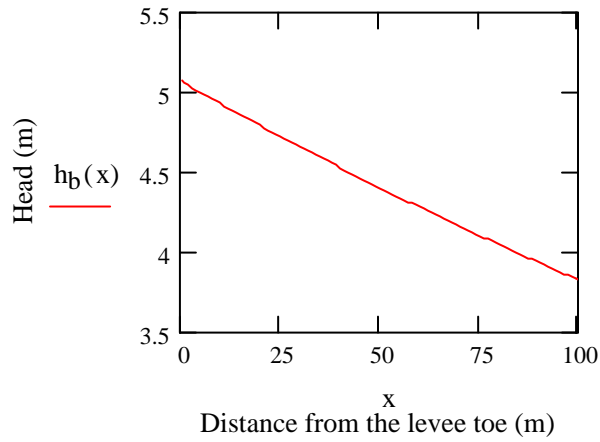
$k_b := 1 \cdot 10^{-6} \frac{\text{m}}{\text{s}}$  hydraulic conductivity of top substratum

$$c := \sqrt{\frac{k_b}{k_f \cdot z_b \cdot d}} \quad x_3 := \frac{1}{c} \quad h_0 := \frac{H \cdot x_3}{x_1 + L_2 + x_3} \quad h_b(x) := h_0 \cdot e^{-c \cdot x}$$

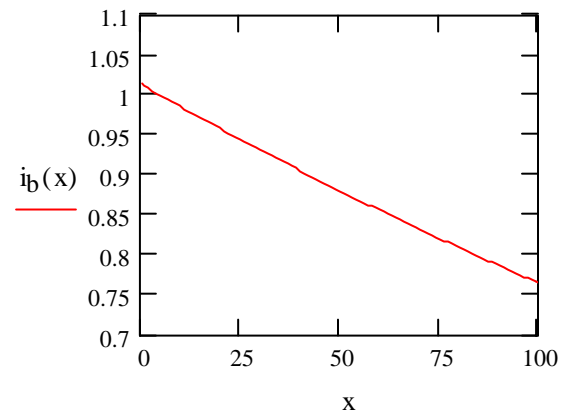
$h_0 = 5.067\text{m}$  head beneath top stratum at landside levee toe

**Figure 6.6**

$x := 0..100$  distance from landside levee toe



$$i_b(x) := \frac{h_0 \cdot e^{-c \cdot x}}{z_b}$$



## Transient Analytical Model by Laplace Transform Method with Leakage out of a Confined Aquifer

$$S := 0.005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day}$$

$$L := 0.2 \quad \omega := \frac{\pi}{60} \quad m := 100 \quad \theta := \text{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}}$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \text{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

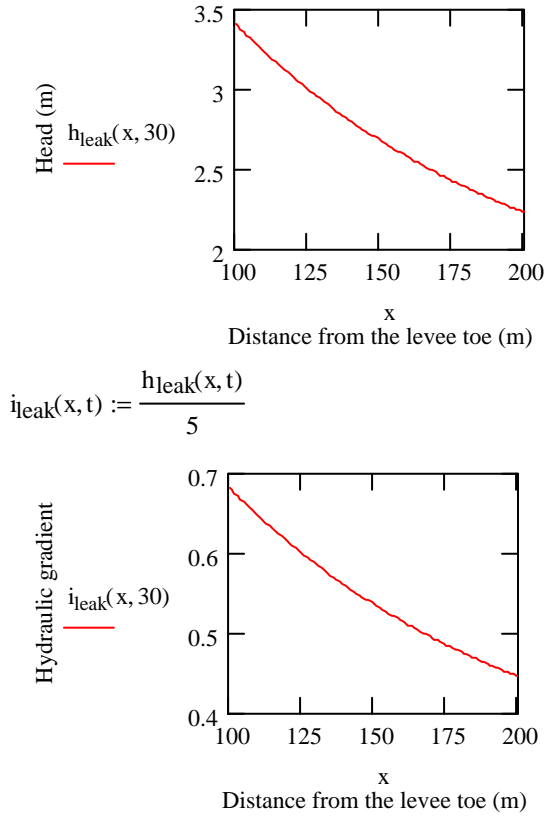
$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_{\text{leak}}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \text{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \text{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**Figure 6.9**

$x := 100..200 \text{ m}$



### Transient Analytical Model by Laplace Transform Method with Leakage out of a Confined Aquifer

$S := 0.005$  dimensionless

$T := 0.02586400 \text{ m}^2/\text{day}$

$L := 0.14$

$\omega := \frac{\pi}{60}$

$m := 100$

$\theta := \text{atan}\left(\frac{S \cdot \omega}{L}\right)$

$a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}}$

$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T}$

$r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$

$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$

$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

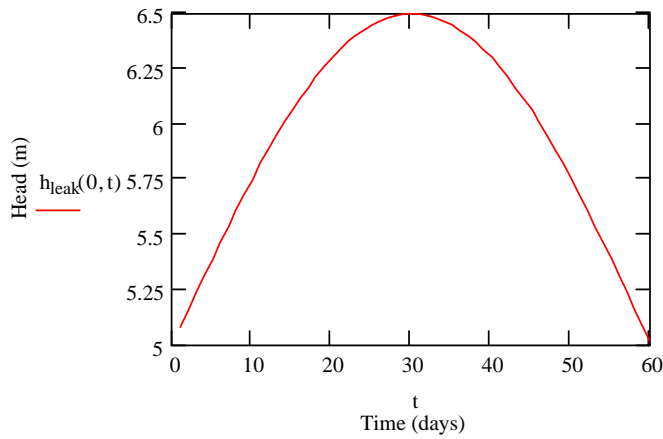
$$F(R, I) := \left[ \text{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$



$$\begin{aligned}
R1(x,t) &:= -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} & I1(t) &:= -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right) \\
R2(x,t) &:= \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} & I2(t) &:= \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right) \\
h_0 &:= 5 \text{ meter} \\
h_1 &:= 1.5 \text{ meter} \\
h_{\text{leak}}(x,t) &:= \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x,t), I1(t)) \dots \right. \right. \\
&\quad \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x,t), I1(t))) \right] \right. \\
&\quad \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x,t), I2(t)) \dots \right. \right. \\
&\quad \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x,t), I2(t))) \right] \right] \\
&\quad + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x,t), I1(t))) \dots \right. \right. \\
&\quad \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x,t), I1(t)) \right] \right. \\
&\quad \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x,t), I2(t))) \dots \right. \right. \\
&\quad \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x,t), I2(t)) \right] \right] \\
&\quad + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \text{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \text{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)
\end{aligned}$$

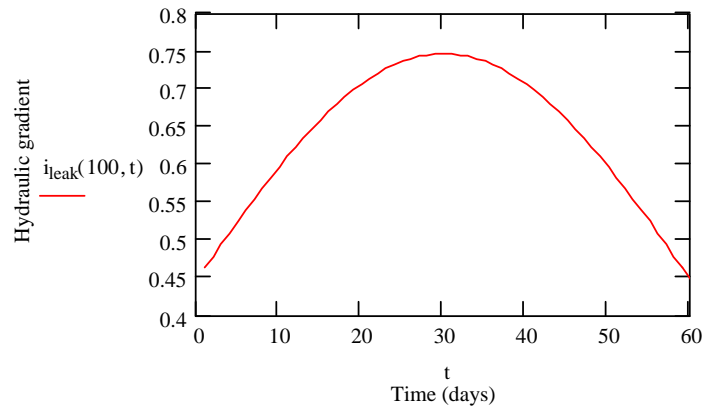
**Figure 6.12**

$t := 0..60$



$$i_{\text{leak}}(x, t) := \frac{h_{\text{leak}}(100, t)}{5}$$

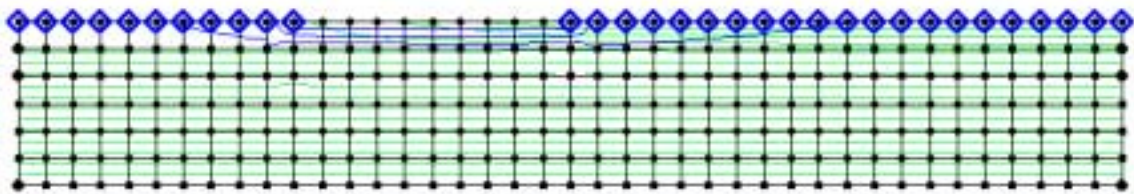
$t := 0..60$



**Fig. 6.7**

### SEEP2D Model

A confined aquifer with a depth of 30 m, and hydraulic conductivities of  $k_h=0.1$  cm/sec,  $k_v=0.0001$  cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head was defined at riverside and landside of the levee. The figure of the model is below:



Note: Node numbers 142 to 282 are located at 5 m below the landside of the levee.

## Model Output

Plane flow problem

Confined aquifer, 30 m.

Number of nodal points----- 287

Number of elements----- 240

Number of diff. materials--- 1

Elevation of datum----- 0.000

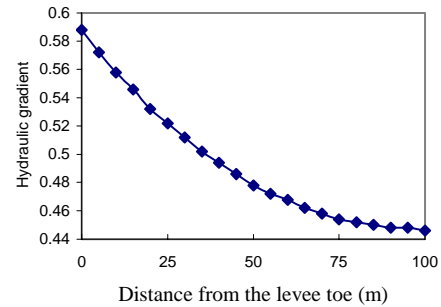
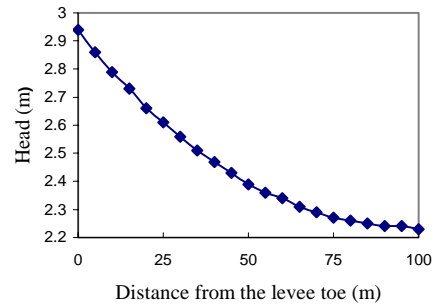
Unsaturated flow option----- 0

Material Properties

30 m depth confined aquifer,  $kh=0.1$  cm/sec,  $kv=0.0001$  cm/sec

Node	Distance (m)	Head	Head-30	i=h/z
142	0	32.94	2.94	0.588
149	5	32.86	2.86	0.572
156	10	32.79	2.79	0.558
163	15	32.73	2.73	0.546
170	20	32.66	2.66	0.532
177	25	32.61	2.61	0.522
184	30	32.56	2.56	0.512
191	35	32.51	2.51	0.502
198	40	32.47	2.47	0.494
205	45	32.43	2.43	0.486
212	50	32.39	2.39	0.478
219	55	32.36	2.36	0.472
226	60	32.34	2.34	0.468
233	65	32.31	2.31	0.462
240	70	32.29	2.29	0.458
247	75	32.27	2.27	0.454
254	80	32.26	2.26	0.452
261	85	32.25	2.25	0.45
268	90	32.24	2.24	0.448
275	95	32.24	2.24	0.448
282	100	32.23	2.23	0.446

Flow = 21.907



Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

### Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	30.00	36.50
2	0	0.00	25.00	0.00
3	0	0.00	20.00	0.00
4	0	0.00	15.00	0.00
5	0	0.00	10.00	0.00
6	0	0.00	5.00	0.00
7	0	0.00	0.00	0.00
8	1	5.00	30.00	36.50
9	0	5.00	25.00	0.00
10	0	5.00	20.00	0.00
11	0	5.00	15.00	0.00
12	0	5.00	10.00	0.00
13	0	5.00	5.00	0.00
14	0	5.00	0.00	0.00
15	1	10.00	30.00	36.50
16	0	10.00	25.00	0.00
17	0	10.00	20.00	0.00

18	0	10.00	15.00	0.00
19	0	10.00	10.00	0.00
20	0	10.00	5.00	0.00
21	0	10.00	0.00	0.00
22	1	15.00	30.00	36.50
23	0	15.00	25.00	0.00
24	0	15.00	20.00	0.00
25	0	15.00	15.00	0.00
26	0	15.00	10.00	0.00
27	0	15.00	5.00	0.00
28	0	15.00	0.00	0.00
29	1	20.00	30.00	36.50
30	0	20.00	25.00	0.00
31	0	20.00	20.00	0.00
32	0	20.00	15.00	0.00
33	0	20.00	10.00	0.00
34	0	20.00	5.00	0.00
35	0	20.00	0.00	0.00
36	1	25.00	30.00	36.50
37	0	25.00	25.00	0.00

38	0	25.00	20.00	0.00
39	0	25.00	15.00	0.00
40	0	25.00	10.00	0.00
41	0	25.00	5.00	0.00
42	0	25.00	0.00	0.00
43	1	30.00	30.00	36.50
44	0	30.00	25.00	0.00
45	0	30.00	20.00	0.00
46	0	30.00	15.00	0.00
47	0	30.00	10.00	0.00
48	0	30.00	5.00	0.00
49	0	30.00	0.00	0.00
50	1	35.00	30.00	36.50
51	0	35.00	25.00	0.00
52	0	35.00	20.00	0.00
53	0	35.00	15.00	0.00
54	0	35.00	10.00	0.00
55	0	35.00	5.00	0.00
56	0	35.00	0.00	0.00
57	1	40.00	30.00	36.50
58	0	40.00	25.00	0.00
59	0	40.00	20.00	0.00
60	0	40.00	15.00	0.00
61	0	40.00	10.00	0.00
62	0	40.00	5.00	0.00
63	0	40.00	0.00	0.00
64	1	45.00	30.00	36.50
65	0	45.00	25.00	0.00
66	0	45.00	20.00	0.00
67	0	45.00	15.00	0.00
68	0	45.00	10.00	0.00
69	0	45.00	5.00	0.00
70	0	45.00	0.00	0.00
71	1	50.00	30.00	36.50
72	0	50.00	25.00	0.00
73	0	50.00	20.00	0.00
74	0	50.00	15.00	0.00
75	0	50.00	10.00	0.00
76	0	50.00	5.00	0.00
77	0	50.00	0.00	0.00
78	0	55.00	30.00	0.00
79	0	55.00	25.00	0.00
80	0	55.00	20.00	0.00
81	0	55.00	15.00	0.00
82	0	55.00	10.00	0.00
83	0	55.00	5.00	0.00
84	0	55.00	0.00	0.00
85	0	60.00	30.00	0.00
86	0	60.00	25.00	0.00
87	0	60.00	20.00	0.00
88	0	60.00	15.00	0.00
89	0	60.00	10.00	0.00
90	0	60.00	5.00	0.00
91	0	60.00	0.00	0.00
92	0	65.00	30.00	0.00
93	0	65.00	25.00	0.00
94	0	65.00	20.00	0.00
95	0	65.00	15.00	0.00
96	0	65.00	10.00	0.00
97	0	65.00	5.00	0.00
98	0	65.00	0.00	0.00
99	0	70.00	30.00	0.00
100	0	70.00	25.00	0.00
101	0	70.00	20.00	0.00
102	0	70.00	15.00	0.00
103	0	70.00	10.00	0.00
104	0	70.00	5.00	0.00
105	0	70.00	0.00	0.00
106	0	75.00	30.00	0.00
107	0	75.00	25.00	0.00

108	0	75.00	20.00	0.00
109	0	75.00	15.00	0.00
110	0	75.00	10.00	0.00
111	0	75.00	5.00	0.00
112	0	75.00	0.00	0.00
113	0	80.00	30.00	0.00
114	0	80.00	25.00	0.00
115	0	80.00	20.00	0.00
116	0	80.00	15.00	0.00
117	0	80.00	10.00	0.00
118	0	80.00	5.00	0.00
119	0	80.00	0.00	0.00
120	0	85.00	30.00	0.00
121	0	85.00	25.00	0.00
122	0	85.00	20.00	0.00
123	0	85.00	15.00	0.00
124	0	85.00	10.00	0.00
125	0	85.00	5.00	0.00
126	0	85.00	0.00	0.00
127	0	90.00	30.00	0.00
128	0	90.00	25.00	0.00
129	0	90.00	20.00	0.00
130	0	90.00	15.00	0.00
131	0	90.00	10.00	0.00
132	0	90.00	5.00	0.00
133	0	90.00	0.00	0.00
134	0	95.00	30.00	0.00
135	0	95.00	25.00	0.00
136	0	95.00	20.00	0.00
137	0	95.00	15.00	0.00
138	0	95.00	10.00	0.00
139	0	95.00	5.00	0.00
140	0	95.00	0.00	0.00
141	1	100.00	30.00	30.00
142	0	100.00	25.00	0.00
143	0	100.00	20.00	0.00
144	0	100.00	15.00	0.00
145	0	100.00	10.00	0.00
146	0	100.00	5.00	0.00
147	0	100.00	0.00	0.00
148	1	105.00	30.00	30.00
149	0	105.00	25.00	0.00
150	0	105.00	20.00	0.00
151	0	105.00	15.00	0.00
152	0	105.00	10.00	0.00
153	0	105.00	5.00	0.00
154	0	105.00	0.00	0.00
155	1	110.00	30.00	30.00
156	0	110.00	25.00	0.00
157	0	110.00	20.00	0.00
158	0	110.00	15.00	0.00
159	0	110.00	10.00	0.00
160	0	110.00	5.00	0.00
161	0	110.00	0.00	0.00
162	1	115.00	30.00	30.00
163	0	115.00	25.00	0.00
164	0	115.00	20.00	0.00
165	0	115.00	15.00	0.00
166	0	115.00	10.00	0.00
167	0	115.00	5.00	0.00
168	0	115.00	0.00	0.00
169	1	120.00	30.00	30.00
170	0	120.00	25.00	0.00
171	0	120.00	20.00	0.00
172	0	120.00	15.00	0.00
173	0	120.00	10.00	0.00
174	0	120.00	5.00	0.00
175	0	120.00	0.00	0.00
176	1	125.00	30.00	30.00
177	0	125.00	25.00	0.00

178	0	125.00	20.00	0.00
179	0	125.00	15.00	0.00
180	0	125.00	10.00	0.00
181	0	125.00	5.00	0.00
182	0	125.00	0.00	0.00
183	1	130.00	30.00	30.00
184	0	130.00	25.00	0.00
185	0	130.00	20.00	0.00
186	0	130.00	15.00	0.00
187	0	130.00	10.00	0.00
188	0	130.00	5.00	0.00
189	0	130.00	0.00	0.00
190	1	135.00	30.00	30.00
191	0	135.00	25.00	0.00
192	0	135.00	20.00	0.00
193	0	135.00	15.00	0.00
194	0	135.00	10.00	0.00
195	0	135.00	5.00	0.00
196	0	135.00	0.00	0.00
197	1	140.00	30.00	30.00
198	0	140.00	25.00	0.00
199	0	140.00	20.00	0.00
200	0	140.00	15.00	0.00
201	0	140.00	10.00	0.00
202	0	140.00	5.00	0.00
203	0	140.00	0.00	0.00
204	1	145.00	30.00	30.00
205	0	145.00	25.00	0.00
206	0	145.00	20.00	0.00
207	0	145.00	15.00	0.00
208	0	145.00	10.00	0.00
209	0	145.00	5.00	0.00
210	0	145.00	0.00	0.00
211	1	150.00	30.00	30.00
212	0	150.00	25.00	0.00
213	0	150.00	20.00	0.00
214	0	150.00	15.00	0.00
215	0	150.00	10.00	0.00
216	0	150.00	5.00	0.00
217	0	150.00	0.00	0.00
218	1	155.00	30.00	30.00
219	0	155.00	25.00	0.00
220	0	155.00	20.00	0.00
221	0	155.00	15.00	0.00
222	0	155.00	10.00	0.00
223	0	155.00	5.00	0.00
224	0	155.00	0.00	0.00
225	1	160.00	30.00	30.00
226	0	160.00	25.00	0.00
227	0	160.00	20.00	0.00
228	0	160.00	15.00	0.00
229	0	160.00	10.00	0.00
230	0	160.00	5.00	0.00
231	0	160.00	0.00	0.00
232	1	165.00	30.00	30.00
233	0	165.00	25.00	0.00
234	0	165.00	20.00	0.00
235	0	165.00	15.00	0.00
236	0	165.00	10.00	0.00
237	0	165.00	5.00	0.00
238	0	165.00	0.00	0.00
239	1	170.00	30.00	30.00
240	0	170.00	25.00	0.00
241	0	170.00	20.00	0.00
242	0	170.00	15.00	0.00
243	0	170.00	10.00	0.00
244	0	170.00	5.00	0.00
245	0	170.00	0.00	0.00
246	1	175.00	30.00	30.00
247	0	175.00	25.00	0.00

248	0	175.00	20.00	0.00
249	0	175.00	15.00	0.00
250	0	175.00	10.00	0.00
251	0	175.00	5.00	0.00
252	0	175.00	0.00	0.00
253	1	180.00	30.00	30.00
254	0	180.00	25.00	0.00
255	0	180.00	20.00	0.00
256	0	180.00	15.00	0.00
257	0	180.00	10.00	0.00
258	0	180.00	5.00	0.00
259	0	180.00	0.00	0.00
260	1	185.00	30.00	30.00
261	0	185.00	25.00	0.00
262	0	185.00	20.00	0.00
263	0	185.00	15.00	0.00
264	0	185.00	10.00	0.00
265	0	185.00	5.00	0.00
266	0	185.00	0.00	0.00
267	1	190.00	30.00	30.00
268	0	190.00	25.00	0.00
269	0	190.00	20.00	0.00
270	0	190.00	15.00	0.00
271	0	190.00	10.00	0.00
272	0	190.00	5.00	0.00
273	0	190.00	0.00	0.00
274	1	195.00	30.00	30.00
275	0	195.00	25.00	0.00
276	0	195.00	20.00	0.00
277	0	195.00	15.00	0.00
278	0	195.00	10.00	0.00
279	0	195.00	5.00	0.00
280	0	195.00	0.00	0.00
281	1	200.00	30.00	30.00
282	0	200.00	25.00	0.00
283	0	200.00	20.00	0.00
284	0	200.00	15.00	0.00
285	0	200.00	10.00	0.00
286	0	200.00	5.00	0.00
287	0	200.00	0.00	0.00

# Nodal Flows and Heads

Node	Head	Percentage of available head	Flow
1	0.3650E+02	100.0 %	0.2234E+00
2	0.3241E+02	37.0 %	
3	0.3242E+02	37.2 %	
4	0.3244E+02	37.5 %	
5	0.3243E+02	37.4 %	0.4473E+00
6	0.3243E+02	37.4 %	
7	0.3243E+02	37.4 %	
8	0.3650E+02	100.0 %	
9	0.3240E+02	37.0 %	0.4488E+00
10	0.3242E+02	37.2 %	
11	0.3244E+02	37.5 %	
12	0.3243E+02	37.4 %	
13	0.3243E+02	37.4 %	0.4488E+00
14	0.3243E+02	37.4 %	
15	0.3650E+02	100.0 %	
16	0.3239E+02	36.8 %	
17	0.3242E+02	37.3 %	0.4488E+00
18	0.3244E+02	37.5 %	
19	0.3243E+02	37.4 %	
20	0.3243E+02	37.4 %	

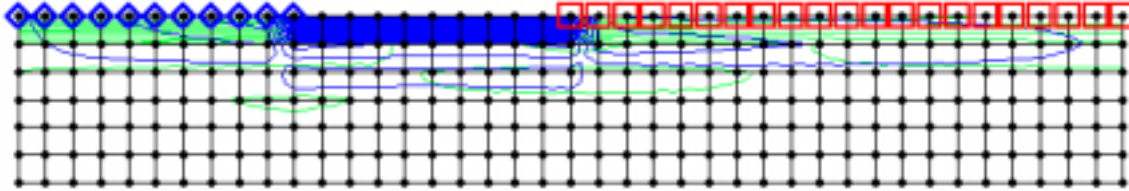
21	0.3243E+02	37.4 %		91	0.3243E+02	37.4 %	
22	0.3650E+02	100.0 %	0.4512E+00	92	0.3450E+02	69.2 %	
23	0.3238E+02	36.6 %		93	0.3236E+02	36.3 %	
24	0.3243E+02	37.3 %		94	0.3245E+02	37.7 %	
25	0.3243E+02	37.5 %		95	0.3243E+02	37.3 %	
26	0.3243E+02	37.4 %		96	0.3243E+02	37.4 %	
27	0.3243E+02	37.4 %		97	0.3243E+02	37.4 %	
28	0.3243E+02	37.4 %		98	0.3243E+02	37.4 %	
29	0.3650E+02	100.0 %	0.4547E+00	99	0.3385E+02	59.3 %	
30	0.3235E+02	36.2 %		100	0.3244E+02	37.6 %	
31	0.3243E+02	37.4 %		101	0.3243E+02	37.4 %	
32	0.3243E+02	37.4 %		102	0.3243E+02	37.4 %	
33	0.3243E+02	37.4 %		103	0.3243E+02	37.4 %	
34	0.3243E+02	37.4 %		104	0.3243E+02	37.4 %	
35	0.3243E+02	37.4 %		105	0.3243E+02	37.4 %	
36	0.3650E+02	100.0 %	0.4592E+00	106	0.3321E+02	49.4 %	
37	0.3232E+02	35.7 %		107	0.3252E+02	38.8 %	
38	0.3244E+02	37.6 %		108	0.3242E+02	37.2 %	
39	0.3243E+02	37.4 %		109	0.3243E+02	37.4 %	
40	0.3243E+02	37.4 %		110	0.3243E+02	37.4 %	
41	0.3243E+02	37.4 %		111	0.3243E+02	37.4 %	
42	0.3243E+02	37.4 %		112	0.3243E+02	37.4 %	
43	0.3650E+02	100.0 %	0.4647E+00	113	0.3258E+02	39.7 %	
44	0.3229E+02	35.2 %		114	0.3260E+02	40.0 %	
45	0.3245E+02	37.7 %		115	0.3240E+02	36.9 %	
46	0.3243E+02	37.4 %		116	0.3244E+02	37.5 %	
47	0.3243E+02	37.4 %		117	0.3243E+02	37.4 %	
48	0.3243E+02	37.4 %		118	0.3243E+02	37.4 %	
49	0.3243E+02	37.4 %		119	0.3243E+02	37.4 %	
50	0.3650E+02	100.0 %	0.4713E+00	120	0.3194E+02	29.9 %	
51	0.3224E+02	34.5 %		121	0.3268E+02	41.2 %	
52	0.3246E+02	37.9 %		122	0.3238E+02	36.7 %	
53	0.3242E+02	37.3 %		123	0.3244E+02	37.5 %	
54	0.3243E+02	37.4 %		124	0.3243E+02	37.4 %	
55	0.3243E+02	37.4 %		125	0.3243E+02	37.4 %	
56	0.3243E+02	37.4 %		126	0.3243E+02	37.4 %	
57	0.3650E+02	100.0 %	0.4790E+00	127	0.3130E+02	20.0 %	
58	0.3219E+02	33.7 %		128	0.3276E+02	42.5 %	
59	0.3248E+02	38.2 %		129	0.3237E+02	36.4 %	
60	0.3242E+02	37.2 %		130	0.3244E+02	37.6 %	
61	0.3243E+02	37.4 %		131	0.3243E+02	37.4 %	
62	0.3243E+02	37.4 %		132	0.3243E+02	37.4 %	
63	0.3243E+02	37.4 %		133	0.3243E+02	37.4 %	
64	0.3650E+02	100.0 %	0.4878E+00	134	0.3066E+02	10.1 %	
65	0.3213E+02	32.8 %		135	0.3285E+02	43.8 %	
66	0.3250E+02	38.4 %		136	0.3235E+02	36.1 %	
67	0.3242E+02	37.2 %		137	0.3245E+02	37.7 %	
68	0.3244E+02	37.5 %		138	0.3243E+02	37.3 %	
69	0.3243E+02	37.4 %		139	0.3243E+02	37.4 %	
70	0.3243E+02	37.4 %		140	0.3243E+02	37.4 %	
71	0.3650E+02	100.0 %	0.1752E+02	141	0.3000E+02	0.0 %	-0.1670E+02
72	0.3207E+02	31.8 %		142	0.3294E+02	45.2 %	
73	0.3252E+02	38.7 %		143	0.3232E+02	35.7 %	
74	0.3241E+02	37.1 %		144	0.3246E+02	37.8 %	
75	0.3244E+02	37.5 %		145	0.3243E+02	37.3 %	
76	0.3243E+02	37.4 %		146	0.3243E+02	37.4 %	
77	0.3243E+02	37.4 %		147	0.3243E+02	37.4 %	
78	0.3582E+02	89.5 %		148	0.3000E+02	0.0 %	-0.3283E+00
79	0.3217E+02	33.4 %		149	0.3286E+02	44.0 %	
80	0.3249E+02	38.3 %		150	0.3234E+02	36.0 %	
81	0.3242E+02	37.2 %		151	0.3245E+02	37.7 %	
82	0.3244E+02	37.5 %		152	0.3243E+02	37.3 %	
83	0.3243E+02	37.4 %		153	0.3243E+02	37.4 %	
84	0.3243E+02	37.4 %		154	0.3243E+02	37.4 %	
85	0.3515E+02	79.2 %		155	0.3000E+02	0.0 %	-0.3177E+00
86	0.3227E+02	35.0 %		156	0.3279E+02	42.9 %	
87	0.3247E+02	38.0 %		157	0.3236E+02	36.3 %	
88	0.3242E+02	37.3 %		158	0.3245E+02	37.6 %	
89	0.3243E+02	37.4 %		159	0.3243E+02	37.4 %	
90	0.3243E+02	37.4 %		160	0.3243E+02	37.4 %	

161	0.3243E+02	37.4 %		230	0.3243E+02	37.4 %	
162	0.3000E+02	0.0 %	-0.3080E+00	231	0.3243E+02	37.4 %	
163	0.3273E+02	41.9 %		232	0.3000E+02	0.0 %	-0.2476E+00
164	0.3238E+02	36.6 %		233	0.3231E+02	35.6 %	
165	0.3244E+02	37.6 %		234	0.3246E+02	37.8 %	
166	0.3243E+02	37.4 %		235	0.3243E+02	37.3 %	
167	0.3243E+02	37.4 %		236	0.3243E+02	37.4 %	
168	0.3243E+02	37.4 %		237	0.3243E+02	37.4 %	
169	0.3000E+02	0.0 %	-0.2990E+00	238	0.3243E+02	37.4 %	
170	0.3266E+02	41.0 %		239	0.3000E+02	0.0 %	-0.2447E+00
171	0.3239E+02	36.8 %		240	0.3229E+02	35.2 %	
172	0.3244E+02	37.5 %		241	0.3246E+02	37.8 %	
173	0.3243E+02	37.4 %		242	0.3243E+02	37.3 %	
174	0.3243E+02	37.4 %		243	0.3243E+02	37.4 %	
175	0.3243E+02	37.4 %		244	0.3243E+02	37.4 %	
176	0.3000E+02	0.0 %	-0.2908E+00	245	0.3243E+02	37.4 %	
177	0.3261E+02	40.1 %		246	0.3000E+02	0.0 %	-0.2422E+00
178	0.3240E+02	37.0 %		247	0.3227E+02	35.0 %	
179	0.3244E+02	37.5 %		248	0.3246E+02	37.9 %	
180	0.3243E+02	37.4 %		249	0.3243E+02	37.3 %	
181	0.3243E+02	37.4 %		250	0.3243E+02	37.4 %	
182	0.3243E+02	37.4 %		251	0.3243E+02	37.4 %	
183	0.3000E+02	0.0 %	-0.2833E+00	252	0.3243E+02	37.4 %	
184	0.3256E+02	39.3 %		253	0.3000E+02	0.0 %	-0.2402E+00
185	0.3241E+02	37.1 %		254	0.3226E+02	34.8 %	
186	0.3243E+02	37.4 %		255	0.3246E+02	37.9 %	
187	0.3243E+02	37.4 %		256	0.3243E+02	37.3 %	
188	0.3243E+02	37.4 %		257	0.3243E+02	37.4 %	
189	0.3243E+02	37.4 %		258	0.3243E+02	37.4 %	
190	0.3000E+02	0.0 %	-0.2764E+00	259	0.3243E+02	37.4 %	
191	0.3251E+02	38.6 %		260	0.3000E+02	0.0 %	-0.2386E+00
192	0.3242E+02	37.3 %		261	0.3225E+02	34.6 %	
193	0.3243E+02	37.4 %		262	0.3247E+02	37.9 %	
194	0.3243E+02	37.4 %		263	0.3243E+02	37.3 %	
195	0.3243E+02	37.4 %		264	0.3243E+02	37.4 %	
196	0.3243E+02	37.4 %		265	0.3243E+02	37.4 %	
197	0.3000E+02	0.0 %	-0.2702E+00	266	0.3243E+02	37.4 %	
198	0.3247E+02	38.0 %		267	0.3000E+02	0.0 %	-0.2375E+00
199	0.3243E+02	37.4 %		268	0.3224E+02	34.5 %	
200	0.3243E+02	37.4 %		269	0.3247E+02	37.9 %	
201	0.3243E+02	37.4 %		270	0.3243E+02	37.3 %	
202	0.3243E+02	37.4 %		271	0.3243E+02	37.4 %	
203	0.3243E+02	37.4 %		272	0.3243E+02	37.4 %	
204	0.3000E+02	0.0 %	-0.2646E+00	273	0.3243E+02	37.4 %	
205	0.3243E+02	37.4 %		274	0.3000E+02	0.0 %	-0.2369E+00
206	0.3244E+02	37.5 %		275	0.3224E+02	34.4 %	
207	0.3243E+02	37.4 %		276	0.3247E+02	38.0 %	
208	0.3243E+02	37.4 %		277	0.3243E+02	37.3 %	
209	0.3243E+02	37.4 %		278	0.3243E+02	37.4 %	
210	0.3243E+02	37.4 %		279	0.3243E+02	37.4 %	
211	0.3000E+02	0.0 %	-0.2595E+00	280	0.3243E+02	37.4 %	
212	0.3239E+02	36.8 %		281	0.3000E+02	0.0 %	-0.1183E+00
213	0.3244E+02	37.6 %		282	0.3223E+02	34.4 %	
214	0.3243E+02	37.4 %		283	0.3247E+02	38.0 %	
215	0.3243E+02	37.4 %		284	0.3243E+02	37.3 %	
216	0.3243E+02	37.4 %		285	0.3243E+02	37.4 %	
217	0.3243E+02	37.4 %		286	0.3243E+02	37.4 %	
218	0.3000E+02	0.0 %	-0.2551E+00	287	0.3243E+02	37.4 %	
219	0.3236E+02	36.4 %					
220	0.3245E+02	37.7 %					
221	0.3243E+02	37.3 %					
222	0.3243E+02	37.4 %					
223	0.3243E+02	37.4 %					
224	0.3243E+02	37.4 %					
225	0.3000E+02	0.0 %	-0.2511E+00				
226	0.3234E+02	35.9 %					
227	0.3245E+02	37.7 %					
228	0.3243E+02	37.3 %					
229	0.3243E+02	37.4 %					

Flow = 2.1907E+01

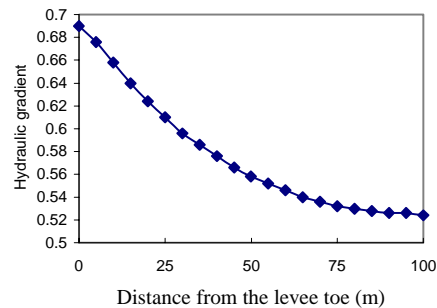
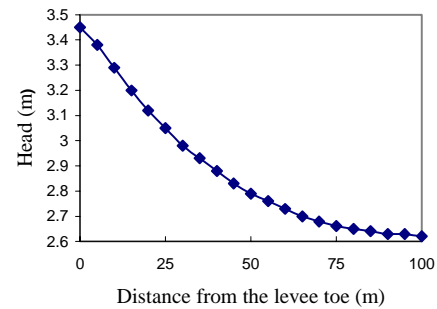
**Fig. 6.11**  
**SEEP2D Model**

An unconfined aquifer with a depth of 30 m, and hydraulic conductivities of  $k_h=0.1$  cm/sec,  $k_v=0.0001$  cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head boundary was defined at riverside and exit face boundary was defined at landside of the levee. The figure of the model is shown below:



30 m depth unconfined, exit face landside levee,  $k_h=0.1$  cm/sec,  $k_v=0.0001$  cm/sec

Node	Distance (m)	Head (m)	Head-30	$i=h/5$
142	0	33.45	3.45	0.69
149	5	33.38	3.38	0.676
156	10	33.29	3.29	0.658
163	15	33.2	3.2	0.64
170	20	33.12	3.12	0.624
177	25	33.05	3.05	0.61
184	30	32.98	2.98	0.596
191	35	32.93	2.93	0.586
198	40	32.88	2.88	0.576
205	45	32.83	2.83	0.566
212	50	32.79	2.79	0.558
219	55	32.76	2.76	0.552
226	60	32.73	2.73	0.546
233	65	32.7	2.7	0.54
240	70	32.68	2.68	0.536
247	75	32.66	2.66	0.532
254	80	32.65	2.65	0.53
261	85	32.64	2.64	0.528
268	90	32.63	2.63	0.526
275	95	32.63	2.63	0.526
282	100	32.62	2.62	0.524



Note: Node numbers 142 to 282 are located at 5 m below the landside of the levee.

### Model Output

Plane flow problem  
30 m exit face  
Number of nodal points----- 287  
Number of elements----- 240  
Number of diff. materials--- 1  
Elevation of datum----- 0.000  
Unsaturation flow option----- 0  
Material Properties  
Mat K1 K2 Angle Uspar1 Uspar2  
1 0.8640E+02 0.8600E-01 0.0000E+00 0.1000E-02 0.0000E+00



Node Point Information									
Node	BC	X	Y	Flow-head					
1	1	0.00	30.00	36.50	62	0	40.00	5.00	0.00
2	0	0.00	25.00	0.00	63	0	40.00	0.00	0.00
3	0	0.00	20.00	0.00	64	1	45.00	30.00	36.50
4	0	0.00	15.00	0.00	65	0	45.00	25.00	0.00
5	0	0.00	10.00	0.00	66	0	45.00	20.00	0.00
6	0	0.00	5.00	0.00	67	0	45.00	15.00	0.00
7	0	0.00	0.00	0.00	68	0	45.00	10.00	0.00
8	1	5.00	30.00	36.50	69	0	45.00	5.00	0.00
9	0	5.00	25.00	0.00	70	0	45.00	0.00	0.00
10	0	5.00	20.00	0.00	71	1	50.00	30.00	36.50
11	0	5.00	15.00	0.00	72	0	50.00	25.00	0.00
12	0	5.00	10.00	0.00	73	0	50.00	20.00	0.00
13	0	5.00	5.00	0.00	74	0	50.00	15.00	0.00
14	0	5.00	0.00	0.00	75	0	50.00	10.00	0.00
15	1	10.00	30.00	36.50	76	0	50.00	5.00	0.00
16	0	10.00	25.00	0.00	77	0	50.00	0.00	0.00
17	0	10.00	20.00	0.00	78	0	55.00	30.00	0.00
18	0	10.00	15.00	0.00	79	0	55.00	25.00	0.00
19	0	10.00	10.00	0.00	80	0	55.00	20.00	0.00
20	0	10.00	5.00	0.00	81	0	55.00	15.00	0.00
21	0	10.00	0.00	0.00	82	0	55.00	10.00	0.00
22	1	15.00	30.00	36.50	83	0	55.00	5.00	0.00
23	0	15.00	25.00	0.00	84	0	55.00	0.00	0.00
24	0	15.00	20.00	0.00	85	0	60.00	30.00	0.00
25	0	15.00	15.00	0.00	86	0	60.00	25.00	0.00
26	0	15.00	10.00	0.00	87	0	60.00	20.00	0.00
27	0	15.00	5.00	0.00	88	0	60.00	15.00	0.00
28	0	15.00	0.00	0.00	89	0	60.00	10.00	0.00
29	1	20.00	30.00	36.50	90	0	60.00	5.00	0.00
30	0	20.00	25.00	0.00	91	0	60.00	0.00	0.00
31	0	20.00	20.00	0.00	92	0	65.00	30.00	0.00
32	0	20.00	15.00	0.00	93	0	65.00	25.00	0.00
33	0	20.00	10.00	0.00	94	0	65.00	20.00	0.00
34	0	20.00	5.00	0.00	95	0	65.00	15.00	0.00
35	0	20.00	0.00	0.00	96	0	65.00	10.00	0.00
36	1	25.00	30.00	36.50	97	0	65.00	5.00	0.00
37	0	25.00	25.00	0.00	98	0	65.00	0.00	0.00
38	0	25.00	20.00	0.00	99	0	70.00	30.00	0.00
39	0	25.00	15.00	0.00	100	0	70.00	25.00	0.00
40	0	25.00	10.00	0.00	101	0	70.00	20.00	0.00
41	0	25.00	5.00	0.00	102	0	70.00	15.00	0.00
42	0	25.00	0.00	0.00	103	0	70.00	10.00	0.00
43	1	30.00	30.00	36.50	104	0	70.00	5.00	0.00
44	0	30.00	25.00	0.00	105	0	70.00	0.00	0.00
45	0	30.00	20.00	0.00	106	0	75.00	30.00	0.00
46	0	30.00	15.00	0.00	107	0	75.00	25.00	0.00
47	0	30.00	10.00	0.00	108	0	75.00	20.00	0.00
48	0	30.00	5.00	0.00	109	0	75.00	15.00	0.00
49	0	30.00	0.00	0.00	110	0	75.00	10.00	0.00
50	1	35.00	30.00	36.50	111	0	75.00	5.00	0.00
51	0	35.00	25.00	0.00	112	0	75.00	0.00	0.00
52	0	35.00	20.00	0.00	113	0	80.00	30.00	0.00
53	0	35.00	15.00	0.00	114	0	80.00	25.00	0.00
54	0	35.00	10.00	0.00	115	0	80.00	20.00	0.00
55	0	35.00	5.00	0.00	116	0	80.00	15.00	0.00
56	0	35.00	0.00	0.00	117	0	80.00	10.00	0.00
57	1	40.00	30.00	36.50	118	0	80.00	5.00	0.00
58	0	40.00	25.00	0.00	119	0	80.00	0.00	0.00
59	0	40.00	20.00	0.00	120	0	85.00	30.00	0.00
60	0	40.00	15.00	0.00	121	0	85.00	25.00	0.00
61	0	40.00	10.00	0.00	122	0	85.00	20.00	0.00
					123	0	85.00	15.00	0.00
					124	0	85.00	10.00	0.00
					125	0	85.00	5.00	0.00
					126	0	85.00	0.00	0.00
					127	0	90.00	30.00	0.00

128	0	90.00	25.00	0.00	194	0	135.00	10.00	0.00
129	0	90.00	20.00	0.00	195	0	135.00	5.00	0.00
130	0	90.00	15.00	0.00	196	0	135.00	0.00	0.00
131	0	90.00	10.00	0.00	197	2	140.00	30.00	0.00
132	0	90.00	5.00	0.00	198	0	140.00	25.00	0.00
133	0	90.00	0.00	0.00	199	0	140.00	20.00	0.00
134	0	95.00	30.00	0.00	200	0	140.00	15.00	0.00
135	0	95.00	25.00	0.00	201	0	140.00	10.00	0.00
136	0	95.00	20.00	0.00	202	0	140.00	5.00	0.00
137	0	95.00	15.00	0.00	203	0	140.00	0.00	0.00
138	0	95.00	10.00	0.00	204	2	145.00	30.00	0.00
139	0	95.00	5.00	0.00	205	0	145.00	25.00	0.00
140	0	95.00	0.00	0.00	206	0	145.00	20.00	0.00
141	2	100.00	30.00	0.00	207	0	145.00	15.00	0.00
142	0	100.00	25.00	0.00	208	0	145.00	10.00	0.00
143	0	100.00	20.00	0.00	209	0	145.00	5.00	0.00
144	0	100.00	15.00	0.00	210	0	145.00	0.00	0.00
145	0	100.00	10.00	0.00	211	2	150.00	30.00	0.00
146	0	100.00	5.00	0.00	212	0	150.00	25.00	0.00
147	0	100.00	0.00	0.00	213	0	150.00	20.00	0.00
148	2	105.00	30.00	0.00	214	0	150.00	15.00	0.00
149	0	105.00	25.00	0.00	215	0	150.00	10.00	0.00
150	0	105.00	20.00	0.00	216	0	150.00	5.00	0.00
151	0	105.00	15.00	0.00	217	0	150.00	0.00	0.00
152	0	105.00	10.00	0.00	218	2	155.00	30.00	0.00
153	0	105.00	5.00	0.00	219	0	155.00	25.00	0.00
154	0	105.00	0.00	0.00	220	0	155.00	20.00	0.00
155	2	110.00	30.00	0.00	221	0	155.00	15.00	0.00
156	0	110.00	25.00	0.00	222	0	155.00	10.00	0.00
157	0	110.00	20.00	0.00	223	0	155.00	5.00	0.00
158	0	110.00	15.00	0.00	224	0	155.00	0.00	0.00
159	0	110.00	10.00	0.00	225	2	160.00	30.00	0.00
160	0	110.00	5.00	0.00	226	0	160.00	25.00	0.00
161	0	110.00	0.00	0.00	227	0	160.00	20.00	0.00
162	2	115.00	30.00	0.00	228	0	160.00	15.00	0.00
163	0	115.00	25.00	0.00	229	0	160.00	10.00	0.00
164	0	115.00	20.00	0.00	230	0	160.00	5.00	0.00
165	0	115.00	15.00	0.00	231	0	160.00	0.00	0.00
166	0	115.00	10.00	0.00	232	2	165.00	30.00	0.00
167	0	115.00	5.00	0.00	233	0	165.00	25.00	0.00
168	0	115.00	0.00	0.00	234	0	165.00	20.00	0.00
169	2	120.00	30.00	0.00	235	0	165.00	15.00	0.00
170	0	120.00	25.00	0.00	236	0	165.00	10.00	0.00
171	0	120.00	20.00	0.00	237	0	165.00	5.00	0.00
172	0	120.00	15.00	0.00	238	0	165.00	0.00	0.00
173	0	120.00	10.00	0.00	239	2	170.00	30.00	0.00
174	0	120.00	5.00	0.00	240	0	170.00	25.00	0.00
175	0	120.00	0.00	0.00	241	0	170.00	20.00	0.00
176	2	125.00	30.00	0.00	242	0	170.00	15.00	0.00
177	0	125.00	25.00	0.00	243	0	170.00	10.00	0.00
178	0	125.00	20.00	0.00	244	0	170.00	5.00	0.00
179	0	125.00	15.00	0.00	245	0	170.00	0.00	0.00
180	0	125.00	10.00	0.00	246	2	175.00	30.00	0.00
181	0	125.00	5.00	0.00	247	0	175.00	25.00	0.00
182	0	125.00	0.00	0.00	248	0	175.00	20.00	0.00
183	2	130.00	30.00	0.00	249	0	175.00	15.00	0.00
184	0	130.00	25.00	0.00	250	0	175.00	10.00	0.00
185	0	130.00	20.00	0.00	251	0	175.00	5.00	0.00
186	0	130.00	15.00	0.00	252	0	175.00	0.00	0.00
187	0	130.00	10.00	0.00	253	2	180.00	30.00	0.00
188	0	130.00	5.00	0.00	254	0	180.00	25.00	0.00
189	0	130.00	0.00	0.00	255	0	180.00	20.00	0.00
190	2	135.00	30.00	0.00	256	0	180.00	15.00	0.00
191	0	135.00	25.00	0.00	257	0	180.00	10.00	0.00
192	0	135.00	20.00	0.00	258	0	180.00	5.00	0.00
193	0	135.00	15.00	0.00	259	0	180.00	0.00	0.00

260	2	185.00	30.00	0.00
261	0	185.00	25.00	0.00
262	0	185.00	20.00	0.00
263	0	185.00	15.00	0.00
264	0	185.00	10.00	0.00
265	0	185.00	5.00	0.00
266	0	185.00	0.00	0.00
267	2	190.00	30.00	0.00
268	0	190.00	25.00	0.00
269	0	190.00	20.00	0.00
270	0	190.00	15.00	0.00
271	0	190.00	10.00	0.00
272	0	190.00	5.00	0.00
273	0	190.00	0.00	0.00
274	2	195.00	30.00	0.00
275	0	195.00	25.00	0.00
276	0	195.00	20.00	0.00
277	0	195.00	15.00	0.00
278	0	195.00	10.00	0.00
279	0	195.00	5.00	0.00
280	0	195.00	0.00	0.00
281	2	200.00	30.00	0.00
282	0	200.00	25.00	0.00
283	0	200.00	20.00	0.00
284	0	200.00	15.00	0.00
285	0	200.00	10.00	0.00
286	0	200.00	5.00	0.00
287	0	200.00	0.00	0.00

#### Nodal Flows and Heads

Node	Head	Percentage of available head	Flow
1	0.3650E+02	100.0 %	0.2029E+00
2	0.3279E+02	43.0 %	
3	0.3285E+02	43.8 %	
4	0.3286E+02	44.0 %	
5	0.3285E+02	43.9 %	
6	0.3285E+02	43.9 %	0.4062E+00
7	0.3285E+02	43.9 %	
8	0.3650E+02	100.0 %	
9	0.3279E+02	42.9 %	
10	0.3285E+02	43.8 %	
11	0.3286E+02	44.0 %	0.4076E+00
12	0.3285E+02	43.9 %	
13	0.3285E+02	43.9 %	
14	0.3285E+02	43.9 %	
15	0.3650E+02	100.0 %	
16	0.3278E+02	42.8 %	0.4098E+00
17	0.3285E+02	43.9 %	
18	0.3286E+02	44.0 %	
19	0.3285E+02	43.9 %	
20	0.3285E+02	43.9 %	
21	0.3285E+02	43.9 %	0.4098E+00
22	0.3650E+02	100.0 %	
23	0.3277E+02	42.6 %	
24	0.3286E+02	43.9 %	
25	0.3286E+02	43.9 %	
26	0.3285E+02	43.9 %	
27	0.3285E+02	43.9 %	

28	0.3285E+02	43.9 %	0.4130E+00
29	0.3650E+02	100.0 %	
30	0.3275E+02	42.2 %	
31	0.3286E+02	44.0 %	
32	0.3285E+02	43.9 %	
33	0.3285E+02	43.9 %	0.4172E+00
34	0.3285E+02	43.9 %	
35	0.3285E+02	43.9 %	
36	0.3650E+02	100.0 %	
37	0.3272E+02	41.8 %	
38	0.3287E+02	44.1 %	0.4223E+00
39	0.3285E+02	43.9 %	
40	0.3285E+02	43.9 %	
41	0.3285E+02	43.9 %	
42	0.3285E+02	43.9 %	
43	0.3650E+02	100.0 %	0.4283E+00
44	0.3268E+02	41.3 %	
45	0.3288E+02	44.3 %	
46	0.3285E+02	43.8 %	
47	0.3285E+02	43.9 %	
48	0.3285E+02	43.9 %	0.4355E+00
49	0.3285E+02	43.9 %	
50	0.3650E+02	100.0 %	
51	0.3264E+02	40.7 %	
52	0.3289E+02	44.5 %	
53	0.3285E+02	43.8 %	0.4436E+00
54	0.3285E+02	43.9 %	
55	0.3285E+02	43.9 %	
56	0.3285E+02	43.9 %	
57	0.3650E+02	100.0 %	
58	0.3260E+02	39.9 %	0.1727E+02
59	0.3291E+02	44.7 %	
60	0.3284E+02	43.7 %	
61	0.3286E+02	43.9 %	
62	0.3285E+02	43.9 %	
63	0.3285E+02	43.9 %	0.1727E+02
64	0.3650E+02	100.0 %	
65	0.3254E+02	39.1 %	
66	0.3292E+02	45.0 %	
67	0.3284E+02	43.7 %	
68	0.3286E+02	44.0 %	0.1727E+02
69	0.3285E+02	43.9 %	
70	0.3285E+02	43.9 %	
71	0.3650E+02	100.0 %	
72	0.3248E+02	38.2 %	
73	0.3294E+02	45.3 %	0.1727E+02
74	0.3283E+02	43.6 %	
75	0.3286E+02	44.0 %	
76	0.3285E+02	43.9 %	
77	0.3285E+02	43.9 %	
78	0.3583E+02	89.6 %	0.1727E+02
79	0.3259E+02	39.9 %	
80	0.3292E+02	44.9 %	
81	0.3284E+02	43.7 %	
82	0.3286E+02	44.0 %	
83	0.3285E+02	43.9 %	0.1727E+02
84	0.3285E+02	43.9 %	
85	0.3517E+02	79.5 %	
86	0.3270E+02	41.5 %	
87	0.3289E+02	44.5 %	
88	0.3284E+02	43.7 %	0.1727E+02
89	0.3286E+02	43.9 %	
90	0.3285E+02	43.9 %	
91	0.3285E+02	43.9 %	
92	0.3452E+02	69.5 %	
93	0.3279E+02	42.9 %	

94	0.3287E+02	44.2 %		160	0.3285E+02	43.9 %	
95	0.3285E+02	43.8 %		161	0.3285E+02	43.9 %	
96	0.3286E+02	43.9 %		162	0.3030E+02	4.6 %	0.2842E-12
97	0.3285E+02	43.9 %		163	0.3320E+02	49.2 %	
98	0.3285E+02	43.9 %		164	0.3279E+02	42.9 %	
99	0.3387E+02	59.6 %		165	0.3287E+02	44.1 %	
100	0.3288E+02	44.3 %		166	0.3285E+02	43.9 %	
101	0.3285E+02	43.9 %		167	0.3285E+02	43.9 %	
102	0.3285E+02	43.9 %		168	0.3285E+02	43.9 %	
103	0.3285E+02	43.9 %		169	0.3043E+02	6.5 %	-0.3979E-12
104	0.3285E+02	43.9 %		170	0.3312E+02	48.0 %	
105	0.3285E+02	43.9 %		171	0.3281E+02	43.2 %	
106	0.3324E+02	49.8 %		172	0.3286E+02	44.0 %	
107	0.3297E+02	45.7 %		173	0.3285E+02	43.9 %	
108	0.3284E+02	43.6 %		174	0.3285E+02	43.9 %	
109	0.3286E+02	43.9 %		175	0.3285E+02	43.9 %	
110	0.3285E+02	43.9 %		176	0.3054E+02	8.3 %	0.1137E-12
111	0.3285E+02	43.9 %		177	0.3305E+02	46.9 %	
112	0.3285E+02	43.9 %		178	0.3282E+02	43.4 %	
113	0.3260E+02	40.0 %		179	0.3286E+02	44.0 %	
114	0.3306E+02	47.0 %		180	0.3285E+02	43.9 %	
115	0.3282E+02	43.3 %		181	0.3285E+02	43.9 %	
116	0.3286E+02	44.0 %		182	0.3285E+02	43.9 %	
117	0.3285E+02	43.9 %		183	0.3065E+02	10.0 %	-0.5684E-13
118	0.3285E+02	43.9 %		184	0.3298E+02	45.9 %	
119	0.3285E+02	43.9 %		185	0.3284E+02	43.7 %	
120	0.3196E+02	30.2 %		186	0.3285E+02	43.9 %	
121	0.3315E+02	48.4 %		187	0.3285E+02	43.9 %	
122	0.3280E+02	43.1 %		188	0.3285E+02	43.9 %	
123	0.3286E+02	44.1 %		189	0.3285E+02	43.9 %	
124	0.3285E+02	43.9 %		190	0.3074E+02	11.4 %	-0.2842E-12
125	0.3285E+02	43.9 %		191	0.3293E+02	45.0 %	
126	0.3285E+02	43.9 %		192	0.3285E+02	43.8 %	
127	0.3132E+02	20.3 %		193	0.3285E+02	43.9 %	
128	0.3324E+02	49.8 %		194	0.3285E+02	43.9 %	
129	0.3278E+02	42.7 %		195	0.3285E+02	43.9 %	
130	0.3287E+02	44.1 %		196	0.3285E+02	43.9 %	
131	0.3285E+02	43.9 %		197	0.3083E+02	12.7 %	-0.2842E-12
132	0.3285E+02	43.9 %		198	0.3288E+02	44.3 %	
133	0.3285E+02	43.9 %		199	0.3286E+02	44.0 %	
134	0.3067E+02	10.2 %		200	0.3285E+02	43.9 %	
135	0.3334E+02	51.4 %		201	0.3285E+02	43.9 %	
136	0.3275E+02	42.4 %		202	0.3285E+02	43.9 %	
137	0.3287E+02	44.2 %		203	0.3285E+02	43.9 %	
138	0.3285E+02	43.8 %		204	0.3090E+02	13.9 %	0.5684E-13
139	0.3285E+02	43.9 %		205	0.3283E+02	43.6 %	
140	0.3285E+02	43.9 %		206	0.3287E+02	44.1 %	
141	0.3000E+02	0.0 %	-0.1698E+02	207	0.3285E+02	43.8 %	
142	0.3345E+02	53.0 %		208	0.3285E+02	43.9 %	
143	0.3273E+02	41.9 %		209	0.3285E+02	43.9 %	
144	0.3288E+02	44.3 %		210	0.3285E+02	43.9 %	
145	0.3285E+02	43.8 %		211	0.3097E+02	14.9 %	-0.5684E-13
146	0.3286E+02	43.9 %		212	0.3279E+02	43.0 %	
147	0.3285E+02	43.9 %		213	0.3287E+02	44.2 %	
148	0.3000E+02	0.0 %	-0.4273E+01	214	0.3285E+02	43.8 %	
149	0.3338E+02	52.1 %		215	0.3285E+02	43.9 %	
150	0.3274E+02	42.2 %		216	0.3285E+02	43.9 %	
151	0.3288E+02	44.3 %		217	0.3285E+02	43.9 %	
152	0.3285E+02	43.8 %		218	0.3103E+02	15.8 %	-0.2274E-12
153	0.3285E+02	43.9 %		219	0.3276E+02	42.4 %	
154	0.3285E+02	43.9 %		220	0.3288E+02	44.3 %	
155	0.3016E+02	2.4 %	0.1137E-12	221	0.3285E+02	43.8 %	
156	0.3329E+02	50.5 %		222	0.3285E+02	43.9 %	
157	0.3277E+02	42.6 %		223	0.3285E+02	43.9 %	
158	0.3287E+02	44.2 %		224	0.3285E+02	43.9 %	
159	0.3285E+02	43.8 %		225	0.3108E+02	16.6 %	0.0000E+00

226	0.3273E+02	42.0 %	
227	0.3288E+02	44.3 %	
228	0.3285E+02	43.8 %	
229	0.3285E+02	43.9 %	
230	0.3285E+02	43.9 %	
231	0.3285E+02	43.9 %	
232	0.3113E+02	17.3 %	0.1137E-12
233	0.3270E+02	41.6 %	
234	0.3288E+02	44.4 %	
235	0.3285E+02	43.8 %	
236	0.3285E+02	43.9 %	
237	0.3285E+02	43.9 %	
238	0.3285E+02	43.9 %	
239	0.3116E+02	17.9 %	0.1137E-12
240	0.3268E+02	41.3 %	
241	0.3289E+02	44.4 %	
242	0.3285E+02	43.8 %	
243	0.3285E+02	43.9 %	
244	0.3285E+02	43.9 %	
245	0.3285E+02	43.9 %	
246	0.3120E+02	18.4 %	0.1137E-12
247	0.3266E+02	41.0 %	
248	0.3289E+02	44.4 %	
249	0.3285E+02	43.8 %	
250	0.3285E+02	43.9 %	
251	0.3285E+02	43.9 %	
252	0.3285E+02	43.9 %	
253	0.3122E+02	18.8 %	0.1705E-12
254	0.3265E+02	40.8 %	
255	0.3289E+02	44.5 %	
256	0.3285E+02	43.8 %	
257	0.3285E+02	43.9 %	
258	0.3285E+02	43.9 %	
259	0.3285E+02	43.9 %	
260	0.3124E+02	19.1 %	-0.1705E-12
261	0.3264E+02	40.6 %	
262	0.3289E+02	44.5 %	
263	0.3285E+02	43.8 %	
264	0.3285E+02	43.9 %	
265	0.3285E+02	43.9 %	
266	0.3285E+02	43.9 %	
267	0.3126E+02	19.3 %	-0.5684E-13
268	0.3263E+02	40.5 %	
269	0.3289E+02	44.5 %	
270	0.3285E+02	43.8 %	
271	0.3285E+02	43.9 %	
272	0.3285E+02	43.9 %	
273	0.3285E+02	43.9 %	
274	0.3127E+02	19.5 %	0.1705E-12
275	0.3263E+02	40.4 %	
276	0.3289E+02	44.5 %	
277	0.3285E+02	43.8 %	
278	0.3285E+02	43.9 %	
279	0.3285E+02	43.9 %	
280	0.3285E+02	43.9 %	
281	0.3127E+02	19.5 %	-0.2274E-12
282	0.3262E+02	40.4 %	
283	0.3289E+02	44.5 %	
284	0.3285E+02	43.8 %	
285	0.3285E+02	43.9 %	
286	0.3285E+02	43.9 %	
287	0.3285E+02	43.9 %	

Flow = 2.1252E+01

## APPENDIX D CALCULATIONS AND GRAPHS IN CHAPTER 7

### Transient Analytical Model by Laplace Transform Method Cumulative Analysis

#### a. $T/S = 5$

$$S := 0.005 \text{ dimensionless}$$

$$T := 0.02586400 \text{ m}^2/\text{day}$$

$$\omega := \frac{\pi}{60}$$

$$r := \omega$$

$$\theta := \frac{\pi}{2}$$

$$a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}}$$

$$m := 100$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \dots$$

$$+ \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}}$$

$$I1(t) := -\sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}}$$

$$I2(t) := \sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$H_0 := 5 \text{ meter}$$

$$H_1 := 1.5 \text{ meter}$$

$$h1a(x, t) := \frac{1}{2} \cdot H_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot H_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \right]$$

$$h_5(x,t) := H_0 \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h1a(x,t)$$

## b. T/S = 18

$$S := 0.005 \text{ dimensionless} \quad T := 0.0986400 \text{ m}^2/\text{day}$$

$$\omega := \frac{\pi}{60} \quad r := \omega \quad \theta := \frac{\pi}{2} \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left[ \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right]$$

$$R1(x,t) := -\sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x,t) := \sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$H_0 := 5 \text{ meter}$$

$$H_1 := 1.5 \text{ meter}$$

$$h1b(x,t) := \frac{1}{2} \cdot H_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x,t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x,t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x,t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x,t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot H_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x,t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x,t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x,t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x,t), I2(t)) \right] \right] \right]$$

$$h18(x,t) := H_0 \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h1b(x,t)$$

**c. T/S = 500**

$$S := 0.00005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day}$$

$$\omega := \frac{\pi}{60} \quad r := \omega \quad \theta := \frac{\pi}{2} \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h1c(x, t) := \frac{1}{2} \cdot H1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot H1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \right]$$

$$h500(x, t) := H0 \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h1c(x, t)$$

**d. T/S = 1800**

$$S := 0.00005 \text{ dimensionless} \quad T := 0.0986400 \text{ m}^2/\text{day}$$

$$\omega := \frac{\pi}{60} \quad r := \omega \quad \theta := \frac{\pi}{2} \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$



$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$H_0 := 5 \text{ meter}$$

$$H_1 := 1.5 \text{ meter}$$

$$h1d(x, t) := \frac{1}{2} \cdot H_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot H_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right]$$

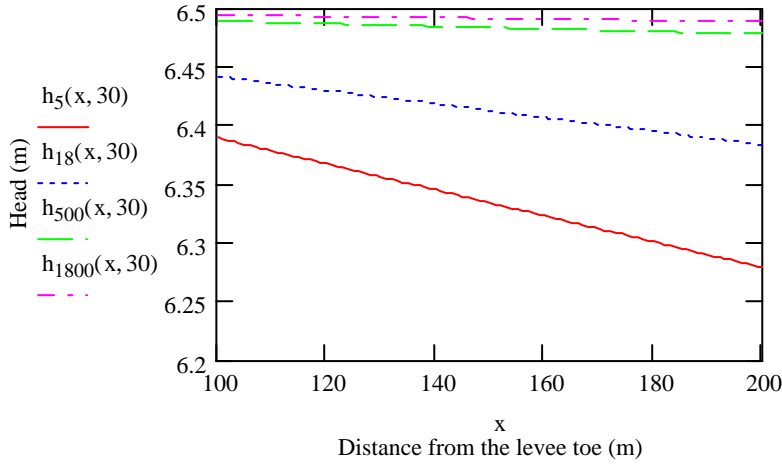
$$h1800(x, t) := H_0 \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h1d(x, t)$$

**Figure 7.2**

**Head vs Time for T/S = 5, 18, 500, 1800**

t := 30 day

x := 100.. 200



$h_5(100, 30) = 6.389$	$h_{18}(100, 30) = 6.442$	$h_{500}(100, 30) = 6.489$	$h_{1800}(100, 30) = 6.494$
$h_5(200, 30) = 6.279$	$h_{18}(200, 30) = 6.383$	$h_{500}(200, 30) = 6.478$	$h_{1800}(200, 30) = 6.488$

$z := 5 \text{ m}$

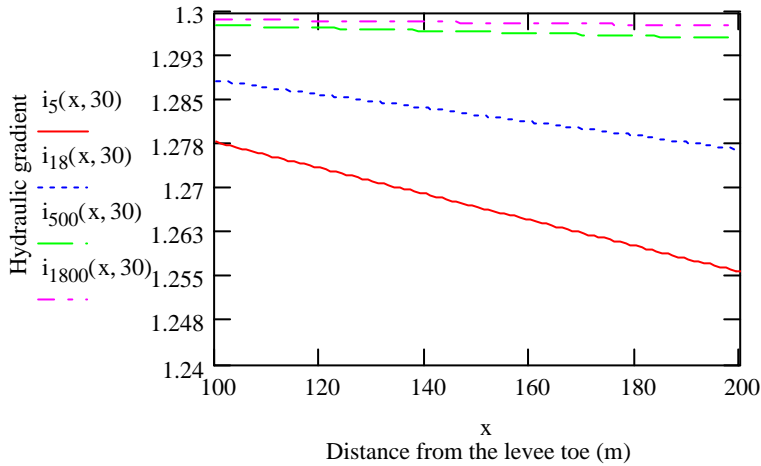
$$i_5(x, t) := h_5(x, t) \cdot \frac{1}{z} \quad i_{500}(x, t) := h_{500}(x, t) \cdot \frac{1}{z}$$

$$i_{1800}(x, t) := h_{1800}(x, t) \cdot \frac{1}{z} \quad i_{18}(x, t) := h_{18}(x, t) \cdot \frac{1}{z}$$

**Figure 7.3**

$t := 30$

$x := 100..200$



$i_5(100, 30) = 1.278$	$i_{18}(100, 30) = 1.288$	$i_{500}(100, 30) = 1.298$	$i_{1800}(100, 30) = 1.299$
$i_5(200, 30) = 1.256$	$i_{18}(200, 30) = 1.277$	$i_{500}(200, 30) = 1.296$	$i_{1800}(200, 30) = 1.298$

## Calculation of Substratum Pressures by the Army Corps Method

EM 1110-2-1913: Design and Construction of Levees details the underseepage analysis. The equations contained in the manual were developed during a study reported in (U.S. Army Engineer Waterways Experiment Station TM 3-424, Appendix A) of piezometric data and seepage measurements along the Lower Mississippi River and confirmed by model studies. Case 7, which is a semipervious top strata both riverside and landside was selected.

$H := 6.5\text{m}$  head at the riverside       $x_1 := 50\text{m}$        $L_2 := 50\text{m}$

$d := 25\text{m}$       assumed thickness of pervious aquifer

$z_b := 5\text{m}$       assumed thickness of top layer

$k_f := 0.1 \cdot 10^{-2} \frac{\text{m}}{\text{s}}$       hydraulic conductivity of pervious substratum

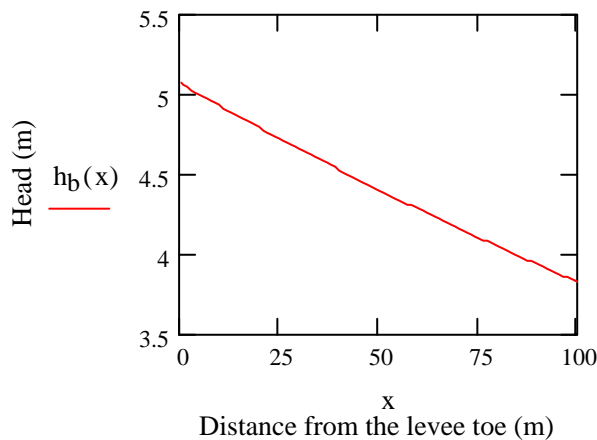
$k_b := 1 \cdot 10^{-6} \frac{\text{m}}{\text{s}}$       hydraulic conductivity of top substratum

$c := \sqrt{\frac{k_b}{k_f \cdot z_b \cdot d}}$        $x_3 := \frac{1}{c}$        $h_0 := \frac{H \cdot x_3}{x_1 + L_2 + x_3}$        $h_b(x) := h_0 \cdot e^{-c \cdot x}$

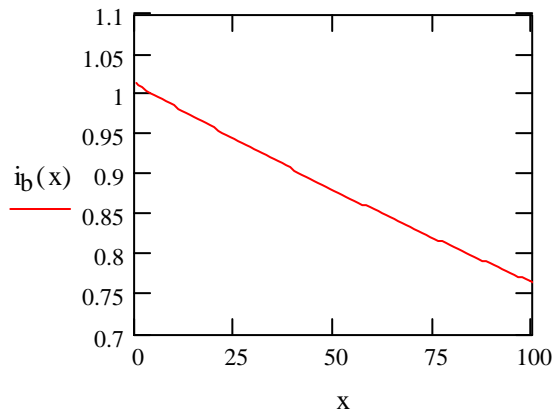
$h_0 = 5.067\text{m}$       head beneath top stratum at landside levee toe

**Figure 7.4**

$x := 0..100$       distance from landside levee toe



$$h_b(x) := \frac{h_0 \cdot e^{-c \cdot x}}{z_b}$$



$H := 6.5\text{m}$  head at the riverside

$x_1 := 50\text{m}$        $L_2 := 50\text{m}$

$d := 45\text{m}$       assumed thickness of pervious aquifer

$z_b := 5\text{m}$       assumed thickness of top layer

$k_f := 0.2 \cdot 10^{-2} \frac{\text{m}}{\text{s}}$       hydraulic conductivity of pervious substratum

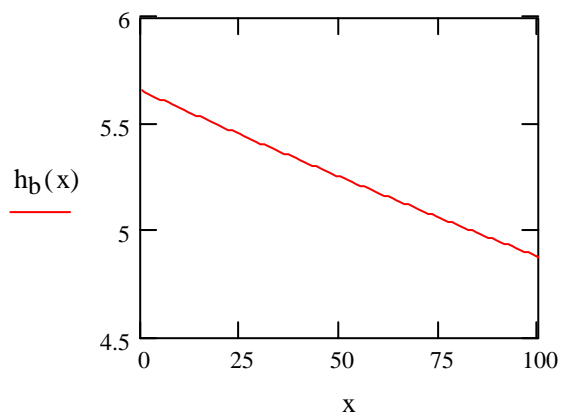
$k_b := 1 \cdot 10^{-6} \frac{\text{m}}{\text{s}}$       hydraulic conductivity of top substratum

$$c := \sqrt{\frac{k_b}{k_f \cdot z_b \cdot d}} \quad x_3 := \frac{1}{c} \quad h_0 := \frac{H \cdot x_3}{x_1 + L_2 + x_3} \quad h_b(x) := h_0 \cdot e^{-c \cdot x}$$

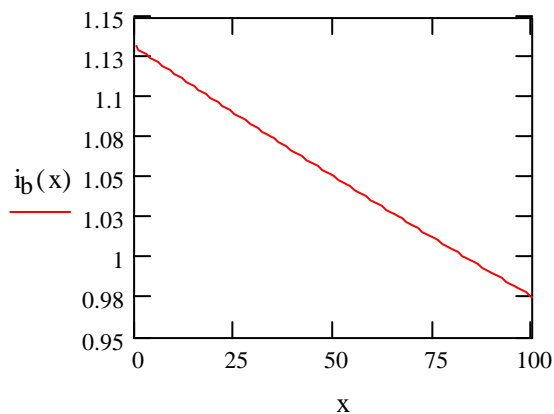
$h_0 = 5.657\text{m}$       head beneath top stratum at landside levee toe

**Figure 7.5**

$x := 0..100$       distance from landside levee toe

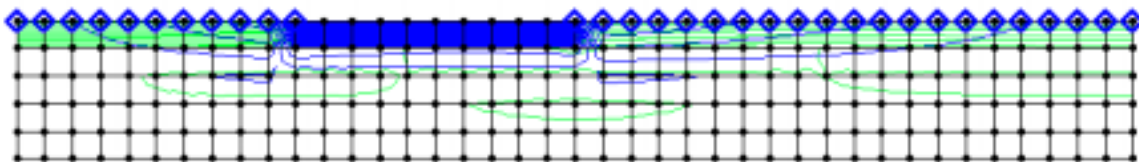


$$i_b(x) := \frac{h_0 \cdot e^{-c \cdot x}}{z_b}$$



**Figure 7.6**  
**SEEP2D Model**

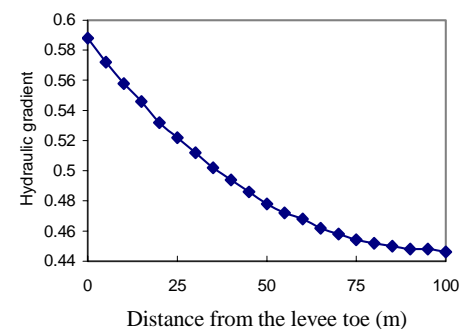
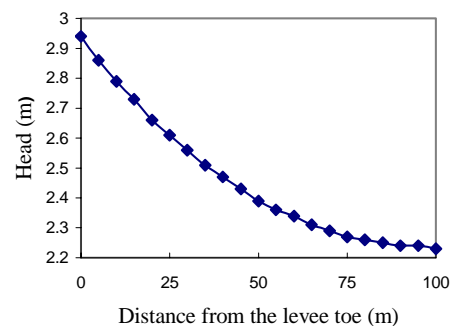
A confined aquifer with a depth of 25 m, and hydraulic conductivities of  $k_h=0.1$  cm/sec,  $k_v=0.0001$  cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head was defined at riverside and landside of the levee. The figure of the model is below:



Cumulative analysis purpose  
25 m confined aquifer,  $T=0.025$  m<sup>2</sup>/sec

Node	Distance (m)	Head (m)	Head-25 (m)	$i=h/5$
122	0	27.94	2.94	0.588
128	5	27.86	2.86	0.572
134	10	27.79	2.79	0.558
140	15	27.73	2.73	0.546
146	20	27.66	2.66	0.532
152	25	27.61	2.61	0.522
158	30	27.56	2.56	0.512
164	35	27.51	2.51	0.502
170	40	27.47	2.47	0.494
176	45	27.43	2.43	0.486
182	50	27.39	2.39	0.478
188	55	27.36	2.36	0.472
194	60	27.34	2.34	0.468
200	65	27.31	2.31	0.462
206	70	27.29	2.29	0.458
212	75	27.27	2.27	0.454
218	80	27.26	2.26	0.452
224	85	27.25	2.25	0.45
230	90	27.24	2.24	0.448
236	95	27.24	2.24	0.448
242	100	27.23	2.23	0.446

Flow = 21.907



Plane flow problem

25 m confined aquifer,  $T=0.025 \text{ m}^2/\text{sec}$

Number of nodal points----- 246

Number of elements----- 200

Number of diff. materials--- 1

Elevation of datum----- 0.000

Unsaturated flow option----- 0

Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

#### Node Point Information

Node	BC	X	Y	Flow-head
------	----	---	---	-----------

1	1	0.00	25.00	31.50
2	0	0.00	20.00	0.00
3	0	0.00	15.00	0.00
4	0	0.00	10.00	0.00
5	0	0.00	5.00	0.00
6	0	0.00	0.00	0.00
7	1	5.00	25.00	31.50
8	0	5.00	20.00	0.00
9	0	5.00	15.00	0.00
10	0	5.00	10.00	0.00
11	0	5.00	5.00	0.00
12	0	5.00	0.00	0.00
13	1	10.00	25.00	31.50
14	0	10.00	20.00	0.00
15	0	10.00	15.00	0.00
16	0	10.00	10.00	0.00
17	0	10.00	5.00	0.00
18	0	10.00	0.00	0.00
19	1	15.00	25.00	31.50
20	0	15.00	20.00	0.00
21	0	15.00	15.00	0.00
22	0	15.00	10.00	0.00
23	0	15.00	5.00	0.00
24	0	15.00	0.00	0.00
25	1	20.00	25.00	31.50
26	0	20.00	20.00	0.00
27	0	20.00	15.00	0.00
28	0	20.00	10.00	0.00
29	0	20.00	5.00	0.00
30	0	20.00	0.00	0.00
31	1	25.00	25.00	31.50
32	0	25.00	20.00	0.00
33	0	25.00	15.00	0.00
34	0	25.00	10.00	0.00
35	0	25.00	5.00	0.00
36	0	25.00	0.00	0.00
37	1	30.00	25.00	31.50
38	0	30.00	20.00	0.00
39	0	30.00	15.00	0.00
40	0	30.00	10.00	0.00
41	0	30.00	5.00	0.00
42	0	30.00	0.00	0.00
43	1	35.00	25.00	31.50
44	0	35.00	20.00	0.00
45	0	35.00	15.00	0.00
46	0	35.00	10.00	0.00
47	0	35.00	5.00	0.00
48	0	35.00	0.00	0.00
49	1	40.00	25.00	31.50
50	0	40.00	20.00	0.00
51	0	40.00	15.00	0.00
52	0	40.00	10.00	0.00
53	0	40.00	5.00	0.00
54	0	40.00	0.00	0.00

55	1	45.00	25.00	31.50
56	0	45.00	20.00	0.00
57	0	45.00	15.00	0.00
58	0	45.00	10.00	0.00
59	0	45.00	5.00	0.00
60	0	45.00	0.00	0.00
61	1	50.00	25.00	31.50
62	0	50.00	20.00	0.00
63	0	50.00	15.00	0.00
64	0	50.00	10.00	0.00
65	0	50.00	5.00	0.00
66	0	50.00	0.00	0.00
67	0	55.00	25.00	0.00
68	0	55.00	20.00	0.00
69	0	55.00	15.00	0.00
70	0	55.00	10.00	0.00
71	0	55.00	5.00	0.00
72	0	55.00	0.00	0.00
73	0	60.00	25.00	0.00
74	0	60.00	20.00	0.00
75	0	60.00	15.00	0.00
76	0	60.00	10.00	0.00
77	0	60.00	5.00	0.00
78	0	60.00	0.00	0.00
79	0	65.00	25.00	0.00
80	0	65.00	20.00	0.00
81	0	65.00	15.00	0.00
82	0	65.00	10.00	0.00
83	0	65.00	5.00	0.00
84	0	65.00	0.00	0.00
85	0	70.00	25.00	0.00
86	0	70.00	20.00	0.00
87	0	70.00	15.00	0.00
88	0	70.00	10.00	0.00
89	0	70.00	5.00	0.00
90	0	70.00	0.00	0.00
91	0	75.00	25.00	0.00
92	0	75.00	20.00	0.00
93	0	75.00	15.00	0.00
94	0	75.00	10.00	0.00
95	0	75.00	5.00	0.00
96	0	75.00	0.00	0.00
97	0	80.00	25.00	0.00
98	0	80.00	20.00	0.00
99	0	80.00	15.00	0.00
100	0	80.00	10.00	0.00
101	0	80.00	5.00	0.00
102	0	80.00	0.00	0.00
103	0	85.00	25.00	0.00
104	0	85.00	20.00	0.00
105	0	85.00	15.00	0.00
106	0	85.00	10.00	0.00
107	0	85.00	5.00	0.00
108	0	85.00	0.00	0.00
109	0	90.00	25.00	0.00
110	0	90.00	20.00	0.00
111	0	90.00	15.00	0.00
112	0	90.00	10.00	0.00
113	0	90.00	5.00	0.00

114	0	90.00	0.00	0.00
115	0	95.00	25.00	0.00
116	0	95.00	20.00	0.00
117	0	95.00	15.00	0.00
118	0	95.00	10.00	0.00
119	0	95.00	5.00	0.00
120	0	95.00	0.00	0.00
121	1	100.00	25.00	25.00
122	0	100.00	20.00	0.00
123	0	100.00	15.00	0.00
124	0	100.00	10.00	0.00
125	0	100.00	5.00	0.00
126	0	100.00	0.00	0.00
127	1	105.00	25.00	25.00
128	0	105.00	20.00	0.00
129	0	105.00	15.00	0.00
130	0	105.00	10.00	0.00
131	0	105.00	5.00	0.00
132	0	105.00	0.00	0.00
133	1	110.00	25.00	25.00
134	0	110.00	20.00	0.00
135	0	110.00	15.00	0.00
136	0	110.00	10.00	0.00
137	0	110.00	5.00	0.00
138	0	110.00	0.00	0.00
139	1	115.00	25.00	25.00
140	0	115.00	20.00	0.00
141	0	115.00	15.00	0.00
142	0	115.00	10.00	0.00
143	0	115.00	5.00	0.00
144	0	115.00	0.00	0.00
145	1	120.00	25.00	25.00
146	0	120.00	20.00	0.00
147	0	120.00	15.00	0.00
148	0	120.00	10.00	0.00
149	0	120.00	5.00	0.00
150	0	120.00	0.00	0.00
151	1	125.00	25.00	25.00
152	0	125.00	20.00	0.00
153	0	125.00	15.00	0.00
154	0	125.00	10.00	0.00
155	0	125.00	5.00	0.00
156	0	125.00	0.00	0.00
157	1	130.00	25.00	25.00
158	0	130.00	20.00	0.00
159	0	130.00	15.00	0.00
160	0	130.00	10.00	0.00
161	0	130.00	5.00	0.00
162	0	130.00	0.00	0.00
163	1	135.00	25.00	25.00
164	0	135.00	20.00	0.00
165	0	135.00	15.00	0.00
166	0	135.00	10.00	0.00
167	0	135.00	5.00	0.00
168	0	135.00	0.00	0.00
169	1	140.00	25.00	25.00
170	0	140.00	20.00	0.00
171	0	140.00	15.00	0.00
172	0	140.00	10.00	0.00
173	0	140.00	5.00	0.00
174	0	140.00	0.00	0.00
175	1	145.00	25.00	25.00
176	0	145.00	20.00	0.00
177	0	145.00	15.00	0.00
178	0	145.00	10.00	0.00
179	0	145.00	5.00	0.00
180	0	145.00	0.00	0.00
181	1	150.00	25.00	25.00
182	0	150.00	20.00	0.00
183	0	150.00	15.00	0.00

184	0	150.00	10.00	0.00
185	0	150.00	5.00	0.00
186	0	150.00	0.00	0.00
187	1	155.00	25.00	25.00
188	0	155.00	20.00	0.00
189	0	155.00	15.00	0.00
190	0	155.00	10.00	0.00
191	0	155.00	5.00	0.00
192	0	155.00	0.00	0.00
193	1	160.00	25.00	25.00
194	0	160.00	20.00	0.00
195	0	160.00	15.00	0.00
196	0	160.00	10.00	0.00
197	0	160.00	5.00	0.00
198	0	160.00	0.00	0.00
199	1	165.00	25.00	25.00
200	0	165.00	20.00	0.00
201	0	165.00	15.00	0.00
202	0	165.00	10.00	0.00
203	0	165.00	5.00	0.00
204	0	165.00	0.00	0.00
205	1	170.00	25.00	25.00
206	0	170.00	20.00	0.00
207	0	170.00	15.00	0.00
208	0	170.00	10.00	0.00
209	0	170.00	5.00	0.00
210	0	170.00	0.00	0.00
211	1	175.00	25.00	25.00
212	0	175.00	20.00	0.00
213	0	175.00	15.00	0.00
214	0	175.00	10.00	0.00
215	0	175.00	5.00	0.00
216	0	175.00	0.00	0.00
217	1	180.00	25.00	25.00
218	0	180.00	20.00	0.00
219	0	180.00	15.00	0.00
220	0	180.00	10.00	0.00
221	0	180.00	5.00	0.00
222	0	180.00	0.00	0.00
223	1	185.00	25.00	25.00
224	0	185.00	20.00	0.00
225	0	185.00	15.00	0.00
226	0	185.00	10.00	0.00
227	0	185.00	5.00	0.00
228	0	185.00	0.00	0.00
229	1	190.00	25.00	25.00
230	0	190.00	20.00	0.00
231	0	190.00	15.00	0.00
232	0	190.00	10.00	0.00
233	0	190.00	5.00	0.00
234	0	190.00	0.00	0.00
235	1	195.00	25.00	25.00
236	0	195.00	20.00	0.00
237	0	195.00	15.00	0.00
238	0	195.00	10.00	0.00
239	0	195.00	5.00	0.00
240	0	195.00	0.00	0.00
241	1	200.00	25.00	25.00
242	0	200.00	20.00	0.00
243	0	200.00	15.00	0.00
244	0	200.00	10.00	0.00
245	0	200.00	5.00	0.00
246	0	200.00	0.00	0.00

#### Nodal Flows and Heads

Node	Head	Percentage of available head	Flow
------	------	---------------------------------	------

1	0.3150E+02	100.0 %	0.2234E+00	71	0.2744E+02	37.5 %	
2	0.2741E+02	37.0 %		72	0.2743E+02	37.4 %	
3	0.2742E+02	37.2 %		73	0.3015E+02	79.2 %	
4	0.2744E+02	37.5 %		74	0.2727E+02	35.0 %	
5	0.2743E+02	37.4 %		75	0.2747E+02	38.0 %	
6	0.2743E+02	37.4 %		76	0.2742E+02	37.3 %	
7	0.3150E+02	100.0 %	0.4473E+00	77	0.2743E+02	37.4 %	
8	0.2740E+02	37.0 %		78	0.2743E+02	37.4 %	
9	0.2742E+02	37.2 %		79	0.2950E+02	69.2 %	
10	0.2744E+02	37.5 %		80	0.2736E+02	36.3 %	
11	0.2743E+02	37.4 %		81	0.2745E+02	37.7 %	
12	0.2743E+02	37.4 %		82	0.2743E+02	37.3 %	
13	0.3150E+02	100.0 %	0.4488E+00	83	0.2743E+02	37.4 %	
14	0.2739E+02	36.8 %		84	0.2743E+02	37.4 %	
15	0.2742E+02	37.3 %		85	0.2885E+02	59.3 %	
16	0.2744E+02	37.5 %		86	0.2744E+02	37.6 %	
17	0.2743E+02	37.4 %		87	0.2743E+02	37.4 %	
18	0.2743E+02	37.4 %		88	0.2743E+02	37.4 %	
19	0.3150E+02	100.0 %	0.4512E+00	89	0.2743E+02	37.4 %	
20	0.2738E+02	36.6 %		90	0.2743E+02	37.4 %	
21	0.2743E+02	37.3 %		91	0.2821E+02	49.4 %	
22	0.2743E+02	37.5 %		92	0.2752E+02	38.8 %	
23	0.2743E+02	37.4 %		93	0.2742E+02	37.2 %	
24	0.2743E+02	37.4 %		94	0.2743E+02	37.4 %	
25	0.3150E+02	100.0 %	0.4547E+00	95	0.2743E+02	37.4 %	
26	0.2735E+02	36.2 %		96	0.2743E+02	37.4 %	
27	0.2743E+02	37.4 %		97	0.2758E+02	39.7 %	
28	0.2743E+02	37.4 %		98	0.2760E+02	40.0 %	
29	0.2743E+02	37.4 %		99	0.2740E+02	36.9 %	
30	0.2743E+02	37.4 %		100	0.2744E+02	37.5 %	
31	0.3150E+02	100.0 %	0.4592E+00	101	0.2743E+02	37.4 %	
32	0.2732E+02	35.7 %		102	0.2743E+02	37.4 %	
33	0.2744E+02	37.6 %		103	0.2694E+02	29.9 %	
34	0.2743E+02	37.4 %		104	0.2768E+02	41.2 %	
35	0.2743E+02	37.4 %		105	0.2738E+02	36.7 %	
36	0.2743E+02	37.4 %		106	0.2744E+02	37.5 %	
37	0.3150E+02	100.0 %	0.4647E+00	107	0.2743E+02	37.4 %	
38	0.2729E+02	35.2 %		108	0.2743E+02	37.4 %	
39	0.2745E+02	37.7 %		109	0.2630E+02	20.0 %	
40	0.2743E+02	37.4 %		110	0.2776E+02	42.5 %	
41	0.2743E+02	37.4 %		111	0.2737E+02	36.4 %	
42	0.2743E+02	37.4 %		112	0.2744E+02	37.6 %	
43	0.3150E+02	100.0 %	0.4713E+00	113	0.2743E+02	37.4 %	
44	0.2724E+02	34.5 %		114	0.2743E+02	37.4 %	
45	0.2746E+02	37.9 %		115	0.2566E+02	10.1 %	
46	0.2742E+02	37.3 %		116	0.2785E+02	43.8 %	
47	0.2743E+02	37.4 %		117	0.2735E+02	36.1 %	
48	0.2743E+02	37.4 %		118	0.2745E+02	37.7 %	
49	0.3150E+02	100.0 %	0.4790E+00	119	0.2743E+02	37.3 %	
50	0.2719E+02	33.7 %		120	0.2743E+02	37.4 %	
51	0.2748E+02	38.2 %		121	0.2500E+02	0.0 %	-0.1670E+02
52	0.2742E+02	37.2 %		122	0.2794E+02	45.2 %	
53	0.2743E+02	37.4 %		123	0.2732E+02	35.7 %	
54	0.2743E+02	37.4 %		124	0.2746E+02	37.8 %	
55	0.3150E+02	100.0 %	0.4878E+00	125	0.2743E+02	37.3 %	
56	0.2713E+02	32.8 %		126	0.2743E+02	37.4 %	
57	0.2750E+02	38.4 %		127	0.2500E+02	0.0 %	-0.3283E+00
58	0.2742E+02	37.2 %		128	0.2786E+02	44.0 %	
59	0.2744E+02	37.5 %		129	0.2734E+02	36.0 %	
60	0.2743E+02	37.4 %		130	0.2745E+02	37.7 %	
61	0.3150E+02	100.0 %	0.1752E+02	131	0.2743E+02	37.3 %	
62	0.2707E+02	31.8 %		132	0.2743E+02	37.4 %	
63	0.2752E+02	38.7 %		133	0.2500E+02	0.0 %	-0.3177E+00
64	0.2741E+02	37.1 %		134	0.2779E+02	42.9 %	
65	0.2744E+02	37.5 %		135	0.2736E+02	36.3 %	
66	0.2743E+02	37.4 %		136	0.2745E+02	37.6 %	
67	0.3082E+02	89.5 %		137	0.2743E+02	37.4 %	
68	0.2717E+02	33.4 %		138	0.2743E+02	37.4 %	
69	0.2749E+02	38.3 %		139	0.2500E+02	0.0 %	-0.3080E+00
70	0.2742E+02	37.2 %		140	0.2773E+02	41.9 %	

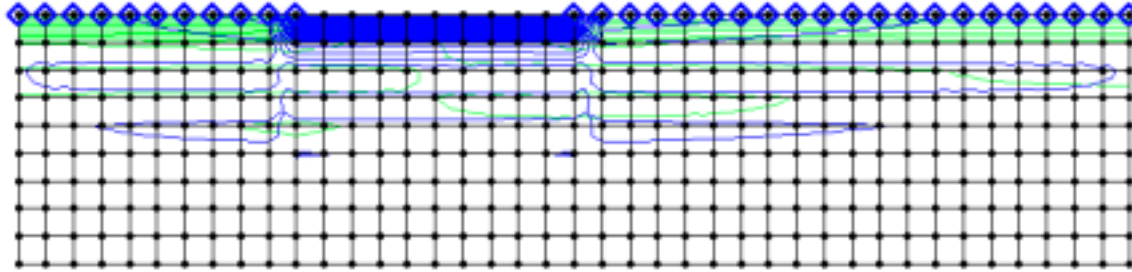


141	0.2738E+02	36.6 %		211	0.2500E+02	0.0 %	-0.2422E+00
142	0.2744E+02	37.6 %		212	0.2727E+02	35.0 %	
143	0.2743E+02	37.4 %		213	0.2746E+02	37.9 %	
144	0.2743E+02	37.4 %		214	0.2743E+02	37.3 %	
145	0.2500E+02	0.0 %	-0.2990E+00	215	0.2743E+02	37.4 %	
146	0.2766E+02	41.0 %		216	0.2743E+02	37.4 %	
147	0.2739E+02	36.8 %		217	0.2500E+02	0.0 %	-0.2402E+00
148	0.2744E+02	37.5 %		218	0.2726E+02	34.8 %	
149	0.2743E+02	37.4 %		219	0.2746E+02	37.9 %	
150	0.2743E+02	37.4 %		220	0.2743E+02	37.3 %	
151	0.2500E+02	0.0 %	-0.2908E+00	221	0.2743E+02	37.4 %	
152	0.2761E+02	40.1 %		222	0.2743E+02	37.4 %	
153	0.2740E+02	37.0 %		223	0.2500E+02	0.0 %	-0.2386E+00
154	0.2744E+02	37.5 %		224	0.2725E+02	34.6 %	
155	0.2743E+02	37.4 %		225	0.2747E+02	37.9 %	
156	0.2743E+02	37.4 %		226	0.2743E+02	37.3 %	
157	0.2500E+02	0.0 %	-0.2833E+00	227	0.2743E+02	37.4 %	
158	0.2756E+02	39.3 %		228	0.2743E+02	37.4 %	
159	0.2741E+02	37.1 %		229	0.2500E+02	0.0 %	-0.2375E+00
160	0.2743E+02	37.4 %		230	0.2724E+02	34.5 %	
161	0.2743E+02	37.4 %		231	0.2747E+02	37.9 %	
162	0.2743E+02	37.4 %		232	0.2743E+02	37.3 %	
163	0.2500E+02	0.0 %	-0.2764E+00	233	0.2743E+02	37.4 %	
164	0.2751E+02	38.6 %		234	0.2743E+02	37.4 %	
165	0.2742E+02	37.3 %		235	0.2500E+02	0.0 %	-0.2369E+00
166	0.2743E+02	37.4 %		236	0.2724E+02	34.4 %	
167	0.2743E+02	37.4 %		237	0.2747E+02	38.0 %	
168	0.2743E+02	37.4 %		238	0.2743E+02	37.3 %	
169	0.2500E+02	0.0 %	-0.2702E+00	239	0.2743E+02	37.4 %	
170	0.2747E+02	38.0 %		240	0.2743E+02	37.4 %	
171	0.2743E+02	37.4 %		241	0.2500E+02	0.0 %	-0.1183E+00
172	0.2743E+02	37.4 %		242	0.2723E+02	34.4 %	
173	0.2743E+02	37.4 %		243	0.2747E+02	38.0 %	
174	0.2743E+02	37.4 %		244	0.2743E+02	37.3 %	
175	0.2500E+02	0.0 %	-0.2646E+00	245	0.2743E+02	37.4 %	
176	0.2743E+02	37.4 %		246	0.2743E+02	37.4 %	
177	0.2744E+02	37.5 %					
178	0.2743E+02	37.4 %					
179	0.2743E+02	37.4 %					
180	0.2743E+02	37.4 %					
181	0.2500E+02	0.0 %	-0.2595E+00				
182	0.2739E+02	36.8 %					
183	0.2744E+02	37.6 %					
184	0.2743E+02	37.4 %					
185	0.2743E+02	37.4 %					
186	0.2743E+02	37.4 %					
187	0.2500E+02	0.0 %	-0.2551E+00				
188	0.2736E+02	36.4 %					
189	0.2745E+02	37.7 %					
190	0.2743E+02	37.3 %					
191	0.2743E+02	37.4 %					
192	0.2743E+02	37.4 %					
193	0.2500E+02	0.0 %	-0.2511E+00				
194	0.2734E+02	35.9 %					
195	0.2745E+02	37.7 %					
196	0.2743E+02	37.3 %					
197	0.2743E+02	37.4 %					
198	0.2743E+02	37.4 %					
199	0.2500E+02	0.0 %	-0.2476E+00				
200	0.2731E+02	35.6 %					
201	0.2746E+02	37.8 %					
202	0.2743E+02	37.3 %					
203	0.2743E+02	37.4 %					
204	0.2743E+02	37.4 %					
205	0.2500E+02	0.0 %	-0.2447E+00				
206	0.2729E+02	35.2 %					
207	0.2746E+02	37.8 %					
208	0.2743E+02	37.3 %					
209	0.2743E+02	37.4 %					
210	0.2743E+02	37.4 %					

Flow = 2.1907E+01

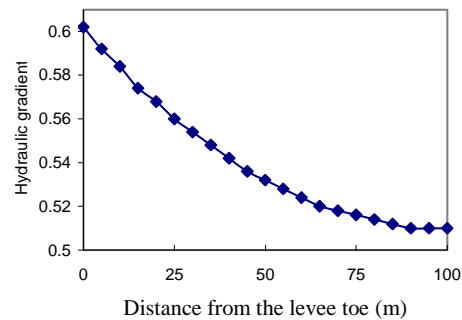
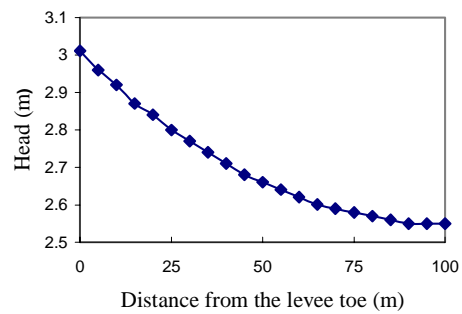
**Figure 7.7**  
**SEEP2D Model**

A confined aquifer with a depth of 45 m, and hydraulic conductivities of  $k_h=0.2$  cm/sec,  $k_v=0.0001$  cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head was defined at riverside and landside of the levee. The figure of the model is below:



Cumulative analysis purpose  
45 m confined aquifer,  $T=0.09$  m<sup>2</sup>/sec

Node	Distance (m)	Head (m)	Head-45 (m)	$i=h/5$
202	0	48.01	3.01	0.602
212	5	47.96	2.96	0.592
222	10	47.92	2.92	0.584
232	15	47.87	2.87	0.574
242	20	47.84	2.84	0.568
252	25	47.8	2.8	0.56
262	30	47.77	2.77	0.554
272	35	47.74	2.74	0.548
282	40	47.71	2.71	0.542
292	45	47.68	2.68	0.536
302	50	47.66	2.66	0.532
312	55	47.64	2.64	0.528
322	60	47.62	2.62	0.524
332	65	47.6	2.6	0.52
342	70	47.59	2.59	0.518
352	75	47.58	2.58	0.516
362	80	47.57	2.57	0.514
372	85	47.56	2.56	0.512
382	90	47.55	2.55	0.51
392	95	47.55	2.55	0.51
402	100	47.55	2.55	0.51



## Model Output

45 m confined aquifer,  $T=0.09 \text{ m}^2/\text{sec}$

Number of nodal points----- 410

Number of elements----- 360

Number of diff. materials--- 1

Elevation of datum----- 0.000

Unsaturated flow option----- 0

Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.1728E+03	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

### Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	45.00	51.50
2	0	0.00	40.00	0.00
3	0	0.00	35.00	0.00
4	0	0.00	30.00	0.00
5	0	0.00	25.00	0.00
6	0	0.00	20.00	0.00
7	0	0.00	15.00	0.00
8	0	0.00	10.00	0.00
9	0	0.00	5.00	0.00
10	0	0.00	0.00	0.00
11	1	5.00	45.00	51.50
12	0	5.00	40.00	0.00
13	0	5.00	35.00	0.00
14	0	5.00	30.00	0.00
15	0	5.00	25.00	0.00
16	0	5.00	20.00	0.00
17	0	5.00	15.00	0.00
18	0	5.00	10.00	0.00
19	0	5.00	5.00	0.00
20	0	5.00	0.00	0.00
21	1	10.00	45.00	51.50
22	0	10.00	40.00	0.00
23	0	10.00	35.00	0.00
24	0	10.00	30.00	0.00
25	0	10.00	25.00	0.00
26	0	10.00	20.00	0.00
27	0	10.00	15.00	0.00
28	0	10.00	10.00	0.00
29	0	10.00	5.00	0.00
30	0	10.00	0.00	0.00
31	1	15.00	45.00	51.50
32	0	15.00	40.00	0.00
33	0	15.00	35.00	0.00
34	0	15.00	30.00	0.00
35	0	15.00	25.00	0.00
36	0	15.00	20.00	0.00
37	0	15.00	15.00	0.00
38	0	15.00	10.00	0.00
39	0	15.00	5.00	0.00
40	0	15.00	0.00	0.00
41	1	20.00	45.00	51.50
42	0	20.00	40.00	0.00
43	0	20.00	35.00	0.00
44	0	20.00	30.00	0.00
45	0	20.00	25.00	0.00
46	0	20.00	20.00	0.00
47	0	20.00	15.00	0.00
48	0	20.00	10.00	0.00
49	0	20.00	5.00	0.00
50	0	20.00	0.00	0.00
51	1	25.00	45.00	51.50

52	0	25.00	40.00	0.00
53	0	25.00	35.00	0.00
54	0	25.00	30.00	0.00
55	0	25.00	25.00	0.00
56	0	25.00	20.00	0.00
57	0	25.00	15.00	0.00
58	0	25.00	10.00	0.00
59	0	25.00	5.00	0.00
60	0	25.00	0.00	0.00
61	1	30.00	45.00	51.50
62	0	30.00	40.00	0.00
63	0	30.00	35.00	0.00
64	0	30.00	30.00	0.00
65	0	30.00	25.00	0.00
66	0	30.00	20.00	0.00
67	0	30.00	15.00	0.00
68	0	30.00	10.00	0.00
69	0	30.00	5.00	0.00
70	0	30.00	0.00	0.00
71	1	35.00	45.00	51.50
72	0	35.00	40.00	0.00
73	0	35.00	35.00	0.00
74	0	35.00	30.00	0.00
75	0	35.00	25.00	0.00
76	0	35.00	20.00	0.00
77	0	35.00	15.00	0.00
78	0	35.00	10.00	0.00
79	0	35.00	5.00	0.00
80	0	35.00	0.00	0.00
81	1	40.00	45.00	51.50
82	0	40.00	40.00	0.00
83	0	40.00	35.00	0.00
84	0	40.00	30.00	0.00
85	0	40.00	25.00	0.00
86	0	40.00	20.00	0.00
87	0	40.00	15.00	0.00
88	0	40.00	10.00	0.00
89	0	40.00	5.00	0.00
90	0	40.00	0.00	0.00
91	1	45.00	45.00	51.50
92	0	45.00	40.00	0.00
93	0	45.00	35.00	0.00
94	0	45.00	30.00	0.00
95	0	45.00	25.00	0.00
96	0	45.00	20.00	0.00
97	0	45.00	15.00	0.00
98	0	45.00	10.00	0.00
99	0	45.00	5.00	0.00
100	0	45.00	0.00	0.00
101	1	50.00	45.00	51.50
102	0	50.00	40.00	0.00
103	0	50.00	35.00	0.00
104	0	50.00	30.00	0.00
105	0	50.00	25.00	0.00
106	0	50.00	20.00	0.00
107	0	50.00	15.00	0.00

108	0	50.00	10.00	0.00
109	0	50.00	5.00	0.00
110	0	50.00	0.00	0.00
111	0	55.00	45.00	0.00
112	0	55.00	40.00	0.00
113	0	55.00	35.00	0.00
114	0	55.00	30.00	0.00
115	0	55.00	25.00	0.00
116	0	55.00	20.00	0.00
117	0	55.00	15.00	0.00
118	0	55.00	10.00	0.00
119	0	55.00	5.00	0.00
120	0	55.00	0.00	0.00
121	0	60.00	45.00	0.00
122	0	60.00	40.00	0.00
123	0	60.00	35.00	0.00
124	0	60.00	30.00	0.00
125	0	60.00	25.00	0.00
126	0	60.00	20.00	0.00
127	0	60.00	15.00	0.00
128	0	60.00	10.00	0.00
129	0	60.00	5.00	0.00
130	0	60.00	0.00	0.00
131	0	65.00	45.00	0.00
132	0	65.00	40.00	0.00
133	0	65.00	35.00	0.00
134	0	65.00	30.00	0.00
135	0	65.00	25.00	0.00
136	0	65.00	20.00	0.00
137	0	65.00	15.00	0.00
138	0	65.00	10.00	0.00
139	0	65.00	5.00	0.00
140	0	65.00	0.00	0.00
141	0	70.00	45.00	0.00
142	0	70.00	40.00	0.00
143	0	70.00	35.00	0.00
144	0	70.00	30.00	0.00
145	0	70.00	25.00	0.00
146	0	70.00	20.00	0.00
147	0	70.00	15.00	0.00
148	0	70.00	10.00	0.00
149	0	70.00	5.00	0.00
150	0	70.00	0.00	0.00
151	0	75.00	45.00	0.00
152	0	75.00	40.00	0.00
153	0	75.00	35.00	0.00
154	0	75.00	30.00	0.00
155	0	75.00	25.00	0.00
156	0	75.00	20.00	0.00
157	0	75.00	15.00	0.00
158	0	75.00	10.00	0.00
159	0	75.00	5.00	0.00
160	0	75.00	0.00	0.00
161	0	80.00	45.00	0.00
162	0	80.00	40.00	0.00
163	0	80.00	35.00	0.00
164	0	80.00	30.00	0.00
165	0	80.00	25.00	0.00
166	0	80.00	20.00	0.00
167	0	80.00	15.00	0.00
168	0	80.00	10.00	0.00
169	0	80.00	5.00	0.00
170	0	80.00	0.00	0.00
171	0	85.00	45.00	0.00
172	0	85.00	40.00	0.00
173	0	85.00	35.00	0.00
174	0	85.00	30.00	0.00
175	0	85.00	25.00	0.00
176	0	85.00	20.00	0.00
177	0	85.00	15.00	0.00

178	0	85.00	10.00	0.00
179	0	85.00	5.00	0.00
180	0	85.00	0.00	0.00
181	0	90.00	45.00	0.00
182	0	90.00	40.00	0.00
183	0	90.00	35.00	0.00
184	0	90.00	30.00	0.00
185	0	90.00	25.00	0.00
186	0	90.00	20.00	0.00
187	0	90.00	15.00	0.00
188	0	90.00	10.00	0.00
189	0	90.00	5.00	0.00
190	0	90.00	0.00	0.00
191	0	95.00	45.00	0.00
192	0	95.00	40.00	0.00
193	0	95.00	35.00	0.00
194	0	95.00	30.00	0.00
195	0	95.00	25.00	0.00
196	0	95.00	20.00	0.00
197	0	95.00	15.00	0.00
198	0	95.00	10.00	0.00
199	0	95.00	5.00	0.00
200	0	95.00	0.00	0.00
201	1	100.00	45.00	45.00
202	0	100.00	40.00	0.00
203	0	100.00	35.00	0.00
204	0	100.00	30.00	0.00
205	0	100.00	25.00	0.00
206	0	100.00	20.00	0.00
207	0	100.00	15.00	0.00
208	0	100.00	10.00	0.00
209	0	100.00	5.00	0.00
210	0	100.00	0.00	0.00
211	1	105.00	45.00	45.00
212	0	105.00	40.00	0.00
213	0	105.00	35.00	0.00
214	0	105.00	30.00	0.00
215	0	105.00	25.00	0.00
216	0	105.00	20.00	0.00
217	0	105.00	15.00	0.00
218	0	105.00	10.00	0.00
219	0	105.00	5.00	0.00
220	0	105.00	0.00	0.00
221	1	110.00	45.00	45.00
222	0	110.00	40.00	0.00
223	0	110.00	35.00	0.00
224	0	110.00	30.00	0.00
225	0	110.00	25.00	0.00
226	0	110.00	20.00	0.00
227	0	110.00	15.00	0.00
228	0	110.00	10.00	0.00
229	0	110.00	5.00	0.00
230	0	110.00	0.00	0.00
231	1	115.00	45.00	45.00
232	0	115.00	40.00	0.00
233	0	115.00	35.00	0.00
234	0	115.00	30.00	0.00
235	0	115.00	25.00	0.00
236	0	115.00	20.00	0.00
237	0	115.00	15.00	0.00
238	0	115.00	10.00	0.00
239	0	115.00	5.00	0.00
240	0	115.00	0.00	0.00
241	1	120.00	45.00	45.00
242	0	120.00	40.00	0.00
243	0	120.00	35.00	0.00
244	0	120.00	30.00	0.00
245	0	120.00	25.00	0.00
246	0	120.00	20.00	0.00
247	0	120.00	15.00	0.00

248	0	120.00	10.00	0.00
249	0	120.00	5.00	0.00
250	0	120.00	0.00	0.00
251	1	125.00	45.00	45.00
252	0	125.00	40.00	0.00
253	0	125.00	35.00	0.00
254	0	125.00	30.00	0.00
255	0	125.00	25.00	0.00
256	0	125.00	20.00	0.00
257	0	125.00	15.00	0.00
258	0	125.00	10.00	0.00
259	0	125.00	5.00	0.00
260	0	125.00	0.00	0.00
261	1	130.00	45.00	45.00
262	0	130.00	40.00	0.00
263	0	130.00	35.00	0.00
264	0	130.00	30.00	0.00
265	0	130.00	25.00	0.00
266	0	130.00	20.00	0.00
267	0	130.00	15.00	0.00
268	0	130.00	10.00	0.00
269	0	130.00	5.00	0.00
270	0	130.00	0.00	0.00
271	1	135.00	45.00	45.00
272	0	135.00	40.00	0.00
273	0	135.00	35.00	0.00
274	0	135.00	30.00	0.00
275	0	135.00	25.00	0.00
276	0	135.00	20.00	0.00
277	0	135.00	15.00	0.00
278	0	135.00	10.00	0.00
279	0	135.00	5.00	0.00
280	0	135.00	0.00	0.00
281	1	140.00	45.00	45.00
282	0	140.00	40.00	0.00
283	0	140.00	35.00	0.00
284	0	140.00	30.00	0.00
285	0	140.00	25.00	0.00
286	0	140.00	20.00	0.00
287	0	140.00	15.00	0.00
288	0	140.00	10.00	0.00
289	0	140.00	5.00	0.00
290	0	140.00	0.00	0.00
291	1	145.00	45.00	45.00
292	0	145.00	40.00	0.00
293	0	145.00	35.00	0.00
294	0	145.00	30.00	0.00
295	0	145.00	25.00	0.00
296	0	145.00	20.00	0.00
297	0	145.00	15.00	0.00
298	0	145.00	10.00	0.00
299	0	145.00	5.00	0.00
300	0	145.00	0.00	0.00
301	1	150.00	45.00	45.00
302	0	150.00	40.00	0.00
303	0	150.00	35.00	0.00
304	0	150.00	30.00	0.00
305	0	150.00	25.00	0.00
306	0	150.00	20.00	0.00
307	0	150.00	15.00	0.00
308	0	150.00	10.00	0.00
309	0	150.00	5.00	0.00
310	0	150.00	0.00	0.00
311	1	155.00	45.00	45.00
312	0	155.00	40.00	0.00
313	0	155.00	35.00	0.00
314	0	155.00	30.00	0.00
315	0	155.00	25.00	0.00
316	0	155.00	20.00	0.00
317	0	155.00	15.00	0.00

318	0	155.00	10.00	0.00
319	0	155.00	5.00	0.00
320	0	155.00	0.00	0.00
321	1	160.00	45.00	45.00
322	0	160.00	40.00	0.00
323	0	160.00	35.00	0.00
324	0	160.00	30.00	0.00
325	0	160.00	25.00	0.00
326	0	160.00	20.00	0.00
327	0	160.00	15.00	0.00
328	0	160.00	10.00	0.00
329	0	160.00	5.00	0.00
330	0	160.00	0.00	0.00
331	1	165.00	45.00	45.00
332	0	165.00	40.00	0.00
333	0	165.00	35.00	0.00
334	0	165.00	30.00	0.00
335	0	165.00	25.00	0.00
336	0	165.00	20.00	0.00
337	0	165.00	15.00	0.00
338	0	165.00	10.00	0.00
339	0	165.00	5.00	0.00
340	0	165.00	0.00	0.00
341	1	170.00	45.00	45.00
342	0	170.00	40.00	0.00
343	0	170.00	35.00	0.00
344	0	170.00	30.00	0.00
345	0	170.00	25.00	0.00
346	0	170.00	20.00	0.00
347	0	170.00	15.00	0.00
348	0	170.00	10.00	0.00
349	0	170.00	5.00	0.00
350	0	170.00	0.00	0.00
351	1	175.00	45.00	45.00
352	0	175.00	40.00	0.00
353	0	175.00	35.00	0.00
354	0	175.00	30.00	0.00
355	0	175.00	25.00	0.00
356	0	175.00	20.00	0.00
357	0	175.00	15.00	0.00
358	0	175.00	10.00	0.00
359	0	175.00	5.00	0.00
360	0	175.00	0.00	0.00
361	1	180.00	45.00	45.00
362	0	180.00	40.00	0.00
363	0	180.00	35.00	0.00
364	0	180.00	30.00	0.00
365	0	180.00	25.00	0.00
366	0	180.00	20.00	0.00
367	0	180.00	15.00	0.00
368	0	180.00	10.00	0.00
369	0	180.00	5.00	0.00
370	0	180.00	0.00	0.00
371	1	185.00	45.00	45.00
372	0	185.00	40.00	0.00
373	0	185.00	35.00	0.00
374	0	185.00	30.00	0.00
375	0	185.00	25.00	0.00
376	0	185.00	20.00	0.00
377	0	185.00	15.00	0.00
378	0	185.00	10.00	0.00
379	0	185.00	5.00	0.00
380	0	185.00	0.00	0.00
381	1	190.00	45.00	45.00
382	0	190.00	40.00	0.00
383	0	190.00	35.00	0.00
384	0	190.00	30.00	0.00
385	0	190.00	25.00	0.00
386	0	190.00	20.00	0.00
387	0	190.00	15.00	0.00

388	0	190.00	10.00	0.00	37	0.4743E+02	37.4 %	
389	0	190.00	5.00	0.00	38	0.4743E+02	37.4 %	
390	0	190.00	0.00	0.00	39	0.4743E+02	37.4 %	
391	1	195.00	45.00	45.00	40	0.4743E+02	37.4 %	
392	0	195.00	40.00	0.00	41	0.5150E+02	100.0 %	0.5102E+00
393	0	195.00	35.00	0.00	42	0.4697E+02	30.3 %	
394	0	195.00	30.00	0.00	43	0.4749E+02	38.3 %	
395	0	195.00	25.00	0.00	44	0.4743E+02	37.3 %	
396	0	195.00	20.00	0.00	45	0.4743E+02	37.5 %	
397	0	195.00	15.00	0.00	46	0.4743E+02	37.4 %	
398	0	195.00	10.00	0.00	47	0.4743E+02	37.4 %	
399	0	195.00	5.00	0.00	48	0.4743E+02	37.4 %	
400	0	195.00	0.00	0.00	49	0.4743E+02	37.4 %	
401	1	200.00	45.00	45.00	50	0.4743E+02	37.4 %	
402	0	200.00	40.00	0.00	51	0.5150E+02	100.0 %	0.5130E+00
403	0	200.00	35.00	0.00	52	0.4695E+02	30.0 %	
404	0	200.00	30.00	0.00	53	0.4750E+02	38.4 %	
405	0	200.00	25.00	0.00	54	0.4743E+02	37.3 %	
406	0	200.00	20.00	0.00	55	0.4743E+02	37.5 %	
407	0	200.00	15.00	0.00	56	0.4743E+02	37.4 %	
408	0	200.00	10.00	0.00	57	0.4743E+02	37.4 %	
409	0	200.00	5.00	0.00	58	0.4743E+02	37.4 %	
410	0	200.00	0.00	0.00	59	0.4743E+02	37.4 %	
Nodal Flows and Heads					60	0.4743E+02	37.4 %	
					61	0.5150E+02	100.0 %	0.5166E+00
					62	0.4693E+02	29.6 %	
					63	0.4750E+02	38.5 %	
					64	0.4742E+02	37.3 %	
					65	0.4744E+02	37.5 %	
					66	0.4743E+02	37.4 %	
					67	0.4743E+02	37.4 %	
					68	0.4743E+02	37.4 %	
					69	0.4743E+02	37.4 %	
					70	0.4743E+02	37.4 %	
					71	0.5150E+02	100.0 %	0.5207E+00
					72	0.4690E+02	29.2 %	
					73	0.4751E+02	38.7 %	
					74	0.4742E+02	37.2 %	
					75	0.4744E+02	37.5 %	
					76	0.4743E+02	37.4 %	
					77	0.4743E+02	37.4 %	
					78	0.4743E+02	37.4 %	
					79	0.4743E+02	37.4 %	
					80	0.4743E+02	37.4 %	
					81	0.5150E+02	100.0 %	0.5256E+00
					82	0.4687E+02	28.7 %	
					83	0.4753E+02	38.9 %	
					84	0.4742E+02	37.2 %	
					85	0.4744E+02	37.5 %	
					86	0.4743E+02	37.4 %	
					87	0.4743E+02	37.4 %	
					88	0.4743E+02	37.4 %	
					89	0.4743E+02	37.4 %	
					90	0.4743E+02	37.4 %	
					91	0.5150E+02	100.0 %	0.5311E+00
					92	0.4683E+02	28.2 %	
					93	0.4754E+02	39.1 %	
					94	0.4741E+02	37.1 %	
					95	0.4744E+02	37.5 %	
					96	0.4743E+02	37.4 %	
					97	0.4743E+02	37.4 %	
					98	0.4743E+02	37.4 %	
					99	0.4743E+02	37.4 %	
					100	0.4743E+02	37.4 %	
					101	0.5150E+02	100.0 %	0.3388E+02
					102	0.4679E+02	27.5 %	
					103	0.4756E+02	39.3 %	
					104	0.4741E+02	37.0 %	
					105	0.4744E+02	37.5 %	
					106	0.4743E+02	37.4 %	

107	0.4743E+02	37.4 %	177	0.4743E+02	37.4 %	
108	0.4743E+02	37.4 %	178	0.4743E+02	37.4 %	
109	0.4743E+02	37.4 %	179	0.4743E+02	37.4 %	
110	0.4743E+02	37.4 %	180	0.4743E+02	37.4 %	
111	0.5083E+02	89.7 %	181	0.4630E+02	20.0 %	
112	0.4692E+02	29.6 %	182	0.4776E+02	42.5 %	
113	0.4753E+02	38.9 %	183	0.4735E+02	36.2 %	
114	0.4741E+02	37.1 %	184	0.4745E+02	37.8 %	
115	0.4744E+02	37.5 %	185	0.4743E+02	37.4 %	
116	0.4743E+02	37.4 %	186	0.4743E+02	37.5 %	
117	0.4743E+02	37.4 %	187	0.4743E+02	37.4 %	
118	0.4743E+02	37.4 %	188	0.4743E+02	37.4 %	
119	0.4743E+02	37.4 %	189	0.4743E+02	37.4 %	
120	0.4743E+02	37.4 %	190	0.4743E+02	37.4 %	
121	0.5017E+02	79.6 %	191	0.4565E+02	10.0 %	
122	0.4705E+02	31.6 %	192	0.4788E+02	44.4 %	
123	0.4750E+02	38.4 %	193	0.4732E+02	35.8 %	
124	0.4742E+02	37.2 %	194	0.4746E+02	37.8 %	
125	0.4744E+02	37.5 %	195	0.4743E+02	37.3 %	
126	0.4743E+02	37.4 %	196	0.4744E+02	37.5 %	
127	0.4743E+02	37.4 %	197	0.4743E+02	37.4 %	
128	0.4743E+02	37.4 %	198	0.4743E+02	37.4 %	
129	0.4743E+02	37.4 %	199	0.4743E+02	37.4 %	
130	0.4743E+02	37.4 %	200	0.4743E+02	37.4 %	
131	0.4952E+02	69.5 %	201	0.4500E+02	0.0 %	-0.3288E+02
132	0.4718E+02	33.5 %	202	0.4801E+02	46.3 %	
133	0.4747E+02	38.0 %	203	0.4730E+02	35.3 %	
134	0.4743E+02	37.3 %	204	0.4747E+02	37.9 %	
135	0.4744E+02	37.5 %	205	0.4743E+02	37.3 %	
136	0.4743E+02	37.4 %	206	0.4744E+02	37.5 %	
137	0.4743E+02	37.4 %	207	0.4743E+02	37.4 %	
138	0.4743E+02	37.4 %	208	0.4743E+02	37.4 %	
139	0.4743E+02	37.4 %	209	0.4743E+02	37.4 %	
140	0.4743E+02	37.4 %	210	0.4743E+02	37.4 %	
141	0.4887E+02	59.6 %	211	0.4500E+02	0.0 %	-0.3430E+00
142	0.4730E+02	35.3 %	212	0.4796E+02	45.5 %	
143	0.4745E+02	37.7 %	213	0.4731E+02	35.6 %	
144	0.4743E+02	37.4 %	214	0.4746E+02	37.9 %	
145	0.4743E+02	37.4 %	215	0.4743E+02	37.3 %	
146	0.4743E+02	37.4 %	216	0.4744E+02	37.5 %	
147	0.4743E+02	37.4 %	217	0.4743E+02	37.4 %	
148	0.4743E+02	37.4 %	218	0.4743E+02	37.4 %	
149	0.4743E+02	37.4 %	219	0.4743E+02	37.4 %	
150	0.4743E+02	37.4 %	220	0.4743E+02	37.4 %	
151	0.4823E+02	49.7 %	221	0.4500E+02	0.0 %	-0.3362E+00
152	0.4741E+02	37.1 %	222	0.4792E+02	44.9 %	
153	0.4742E+02	37.3 %	223	0.4733E+02	35.9 %	
154	0.4744E+02	37.5 %	224	0.4746E+02	37.8 %	
155	0.4743E+02	37.4 %	225	0.4743E+02	37.4 %	
156	0.4743E+02	37.4 %	226	0.4743E+02	37.5 %	
157	0.4743E+02	37.4 %	227	0.4743E+02	37.4 %	
158	0.4743E+02	37.4 %	228	0.4743E+02	37.4 %	
159	0.4743E+02	37.4 %	229	0.4743E+02	37.4 %	
160	0.4743E+02	37.4 %	230	0.4743E+02	37.4 %	
161	0.4759E+02	39.8 %	231	0.4500E+02	0.0 %	-0.3298E+00
162	0.4753E+02	38.9 %	232	0.4787E+02	44.2 %	
163	0.4740E+02	36.9 %	233	0.4735E+02	36.1 %	
164	0.4744E+02	37.6 %	234	0.4745E+02	37.7 %	
165	0.4743E+02	37.4 %	235	0.4743E+02	37.4 %	
166	0.4743E+02	37.5 %	236	0.4743E+02	37.5 %	
167	0.4743E+02	37.4 %	237	0.4743E+02	37.4 %	
168	0.4743E+02	37.4 %	238	0.4743E+02	37.4 %	
169	0.4743E+02	37.4 %	239	0.4743E+02	37.4 %	
170	0.4743E+02	37.4 %	240	0.4743E+02	37.4 %	
171	0.4694E+02	29.9 %	241	0.4500E+02	0.0 %	-0.3239E+00
172	0.4765E+02	40.7 %	242	0.4784E+02	43.6 %	
173	0.4738E+02	36.5 %	243	0.4736E+02	36.3 %	
174	0.4745E+02	37.7 %	244	0.4745E+02	37.7 %	
175	0.4743E+02	37.4 %	245	0.4743E+02	37.4 %	
176	0.4743E+02	37.5 %	246	0.4743E+02	37.5 %	

247	0.4743E+02	37.4 %		317	0.4743E+02	37.4 %	
248	0.4743E+02	37.4 %		318	0.4743E+02	37.4 %	
249	0.4743E+02	37.4 %		319	0.4743E+02	37.4 %	
250	0.4743E+02	37.4 %		320	0.4743E+02	37.4 %	
251	0.4500E+02	0.0 %	-0.3184E+00	321	0.4500E+02	0.0 %	-0.2910E+00
252	0.4780E+02	43.1 %		322	0.4762E+02	40.3 %	
253	0.4737E+02	36.5 %		323	0.4743E+02	37.4 %	
254	0.4745E+02	37.6 %		324	0.4743E+02	37.4 %	
255	0.4743E+02	37.4 %		325	0.4744E+02	37.5 %	
256	0.4743E+02	37.4 %		326	0.4743E+02	37.4 %	
257	0.4743E+02	37.4 %		327	0.4743E+02	37.4 %	
258	0.4743E+02	37.4 %		328	0.4743E+02	37.4 %	
259	0.4743E+02	37.4 %		329	0.4743E+02	37.4 %	
260	0.4743E+02	37.4 %		330	0.4743E+02	37.4 %	
261	0.4500E+02	0.0 %	-0.3133E+00	331	0.4500E+02	0.0 %	-0.2886E+00
262	0.4777E+02	42.6 %		332	0.4760E+02	40.0 %	
263	0.4738E+02	36.7 %		333	0.4744E+02	37.5 %	
264	0.4744E+02	37.6 %		334	0.4743E+02	37.4 %	
265	0.4743E+02	37.4 %		335	0.4744E+02	37.5 %	
266	0.4743E+02	37.4 %		336	0.4743E+02	37.4 %	
267	0.4743E+02	37.4 %		337	0.4743E+02	37.4 %	
268	0.4743E+02	37.4 %		338	0.4743E+02	37.4 %	
269	0.4743E+02	37.4 %		339	0.4743E+02	37.4 %	
270	0.4743E+02	37.4 %		340	0.4743E+02	37.4 %	
271	0.4500E+02	0.0 %	-0.3087E+00	341	0.4500E+02	0.0 %	-0.2865E+00
272	0.4774E+02	42.1 %		342	0.4759E+02	39.8 %	
273	0.4739E+02	36.8 %		343	0.4744E+02	37.5 %	
274	0.4744E+02	37.5 %		344	0.4743E+02	37.4 %	
275	0.4743E+02	37.4 %		345	0.4744E+02	37.5 %	
276	0.4743E+02	37.4 %		346	0.4743E+02	37.4 %	
277	0.4743E+02	37.4 %		347	0.4743E+02	37.4 %	
278	0.4743E+02	37.4 %		348	0.4743E+02	37.4 %	
279	0.4743E+02	37.4 %		349	0.4743E+02	37.4 %	
280	0.4743E+02	37.4 %		350	0.4743E+02	37.4 %	
281	0.4500E+02	0.0 %	-0.3044E+00	351	0.4500E+02	0.0 %	-0.2847E+00
282	0.4771E+02	41.6 %		352	0.4758E+02	39.6 %	
283	0.4740E+02	37.0 %		353	0.4744E+02	37.6 %	
284	0.4744E+02	37.5 %		354	0.4743E+02	37.3 %	
285	0.4743E+02	37.4 %		355	0.4744E+02	37.5 %	
286	0.4743E+02	37.4 %		356	0.4743E+02	37.4 %	
287	0.4743E+02	37.4 %		357	0.4743E+02	37.4 %	
288	0.4743E+02	37.4 %		358	0.4743E+02	37.4 %	
289	0.4743E+02	37.4 %		359	0.4743E+02	37.4 %	
290	0.4743E+02	37.4 %		360	0.4743E+02	37.4 %	
291	0.4500E+02	0.0 %	-0.3005E+00	361	0.4500E+02	0.0 %	-0.2832E+00
292	0.4768E+02	41.2 %		362	0.4757E+02	39.5 %	
293	0.4741E+02	37.1 %		363	0.4745E+02	37.6 %	
294	0.4744E+02	37.5 %		364	0.4743E+02	37.3 %	
295	0.4743E+02	37.4 %		365	0.4744E+02	37.5 %	
296	0.4743E+02	37.4 %		366	0.4743E+02	37.4 %	
297	0.4743E+02	37.4 %		367	0.4743E+02	37.4 %	
298	0.4743E+02	37.4 %		368	0.4743E+02	37.4 %	
299	0.4743E+02	37.4 %		369	0.4743E+02	37.4 %	
300	0.4743E+02	37.4 %		370	0.4743E+02	37.4 %	
301	0.4500E+02	0.0 %	-0.2970E+00	371	0.4500E+02	0.0 %	-0.2821E+00
302	0.4766E+02	40.9 %		372	0.4756E+02	39.4 %	
303	0.4742E+02	37.2 %		373	0.4745E+02	37.7 %	
304	0.4743E+02	37.4 %		374	0.4743E+02	37.3 %	
305	0.4743E+02	37.5 %		375	0.4744E+02	37.5 %	
306	0.4743E+02	37.4 %		376	0.4743E+02	37.4 %	
307	0.4743E+02	37.4 %		377	0.4743E+02	37.4 %	
308	0.4743E+02	37.4 %		378	0.4743E+02	37.4 %	
309	0.4743E+02	37.4 %		379	0.4743E+02	37.4 %	
310	0.4743E+02	37.4 %		380	0.4743E+02	37.4 %	
311	0.4500E+02	0.0 %	-0.2938E+00	381	0.4500E+02	0.0 %	-0.2813E+00
312	0.4764E+02	40.6 %		382	0.4755E+02	39.3 %	
313	0.4743E+02	37.3 %		383	0.4745E+02	37.7 %	
314	0.4743E+02	37.4 %		384	0.4743E+02	37.3 %	
315	0.4743E+02	37.5 %		385	0.4744E+02	37.5 %	
316	0.4743E+02	37.4 %		386	0.4743E+02	37.4 %	



387	0.4743E+02	37.4 %	
388	0.4743E+02	37.4 %	
389	0.4743E+02	37.4 %	
390	0.4743E+02	37.4 %	
391	0.4500E+02	0.0 %	-0.2808E+00
392	0.4755E+02	39.2 %	
393	0.4745E+02	37.7 %	
394	0.4743E+02	37.3 %	
395	0.4744E+02	37.5 %	
396	0.4743E+02	37.4 %	
397	0.4743E+02	37.4 %	
398	0.4743E+02	37.4 %	
399	0.4743E+02	37.4 %	
400	0.4743E+02	37.4 %	
401	0.4500E+02	0.0 %	-0.1403E+00
402	0.4755E+02	39.2 %	
403	0.4745E+02	37.7 %	
404	0.4743E+02	37.3 %	
405	0.4744E+02	37.5 %	
406	0.4743E+02	37.4 %	
407	0.4743E+02	37.4 %	
408	0.4743E+02	37.4 %	
409	0.4743E+02	37.4 %	
410	0.4743E+02	37.4 %	

Flow = 3.8768E+01

## Transient Analytical Model with Laplace Transform Method with Leakage out of a Confined Aquifer for Cumulative Analysis

### a. $T/S = 5$

$$S := 0.005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day}$$

$$L := 0.2 \quad \omega := \frac{\pi}{60} \quad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_5(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**b. T/S = 18**

$$S := 0.005 \text{ dimensionless} \quad T := 0.0986400 \text{ m}^2/\text{day}$$

$$L := 0.2 \quad \omega := \frac{\pi}{60} \quad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_{18}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**c. T/S = 500**

$$S := 0.00005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day}$$

$$L := 0.2 \quad \omega := \frac{\pi}{60} \quad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_{500}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**d. T/S = 1800**

$$S := 0.00005 \text{ dimensionless} \quad T := 0.0986400 \text{ m}^2/\text{day}$$

$$L := 0.2 \quad \omega := \frac{\pi}{60} \quad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

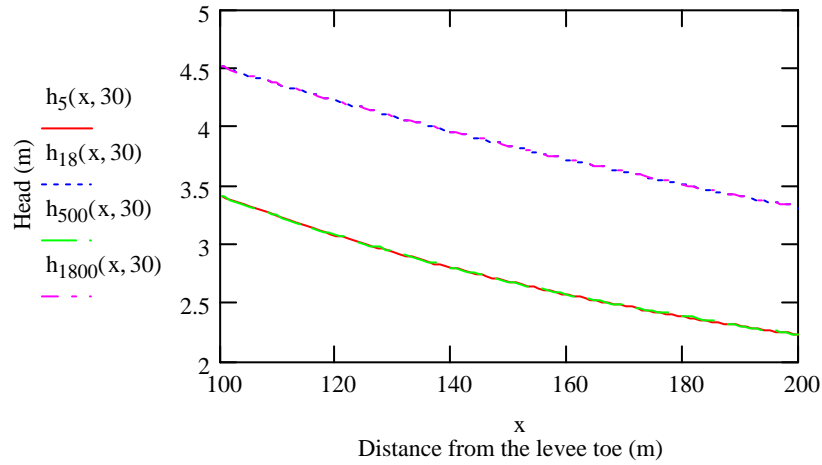
$$h_{1800}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

## Head Development with $L=0.36 \text{ 1/d}$ , for different T/S ratios, $a,b,c,d=5,18,500,1800$

**Figure 7.8**

$t := 30 \text{ day}$

$x := 100..200 \text{ m}$



$$h_5(100, 30) = 3.408$$

$$h_{18}(100, 30) = 4.51$$

$$h_{500}(100, 30) = 3.41$$

$$h_{1800}(100, 30) = 4.511$$

$$h_5(200, 30) = 2.225$$

$$h_{18}(200, 30) = 3.312$$

$$h_{500}(200, 30) = 2.229$$

$$h_{1800}(200, 30) = 3.313$$

$z := 5 \text{ m}$

$$i_5(x, t) := \frac{1}{z} \cdot h_5(x, t)$$

$$i_{18}(x, t) := \frac{1}{z} \cdot h_{18}(x, t)$$

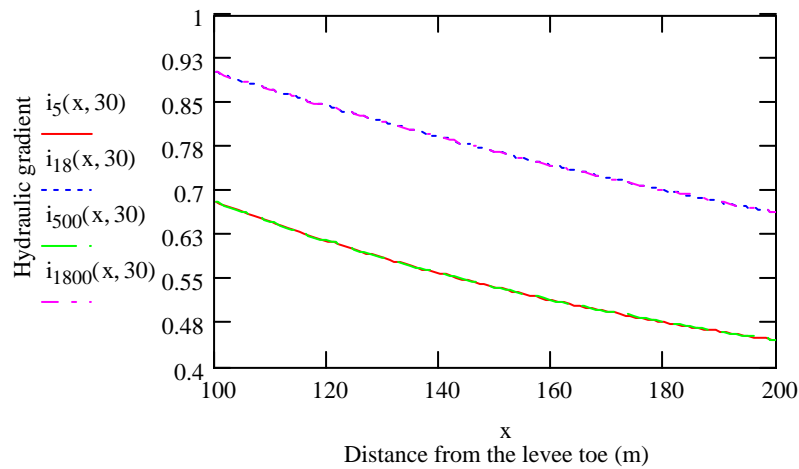
$$i_{500}(x, t) := \frac{1}{z} \cdot h_{500}(x, t)$$

$$i_{1800}(x, t) := \frac{1}{z} \cdot h_{1800}(x, t)$$

**Figure 7.9**

$t := 30$

$x := 100..200$



$$i_5(100, 30) = 0.682$$

$$i_{18}(100, 30) = 0.902$$

$$i_{500}(100, 30) = 0.682$$

$$i_{1800}(100, 30) = 0.902$$

$$i_5(200, 30) = 0.445$$

$$i_{18}(200, 30) = 0.662$$

$$i_{500}(200, 30) = 0.446$$

$$i_{1800}(200, 30) = 0.663$$

## Head Development with $L=0.36$ 1/d, for different T/S ratios, a,b,c,d=5,18,500,1800

### a. T/S = 5

$$S := 0.005 \text{ dimensionless}$$

$$T := 0.02586400 \text{ m}^2/\text{day}$$

$$L := 0.36$$

$$\omega := \frac{\pi}{60}$$

$$\theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right)$$

$$a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T}$$

$$r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}}$$

$$I1(t) := -\sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1} \cdot t \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}}$$

$$I2(t) := \sqrt{r1} \cdot t \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_5(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**b. T/S = 18**

$$S := 0.005 \text{ dimensionless} \quad T := 0.0986400 \text{ m}^2/\text{day}$$

$$L := 0.36 \quad \omega := \frac{\pi}{60} \quad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_{18}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$



**c. T/S = 500**

$$S := 0.00005 \text{ dimensionless} \quad T := 0.02586400 \text{ m}^2/\text{day}$$

$$L := 0.36 \quad \omega := \frac{\pi}{60} \quad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

$$h_1 := 1.5 \text{ meter}$$

$$h_{500}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right] \dots \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right] \dots \right. \\ \left. + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right] \dots \right. \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right] \dots \right. \\ \left. + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right) \right]$$

**d. T/S = 1800**

$$S := 0.00005 \text{ dimensionless} \quad T := 0.0986400 \text{ m}^2/\text{day}$$

$$L := 0.36 \quad \omega := \frac{\pi}{60} \quad \theta := \text{atan}\left(\frac{S \cdot \omega}{L}\right) \quad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \quad m := 100$$

$$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \quad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$$

$$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[ \text{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I)) \right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left( \sum_{n=1}^m \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n) \right)$$

$$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \quad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \text{ meter}$$

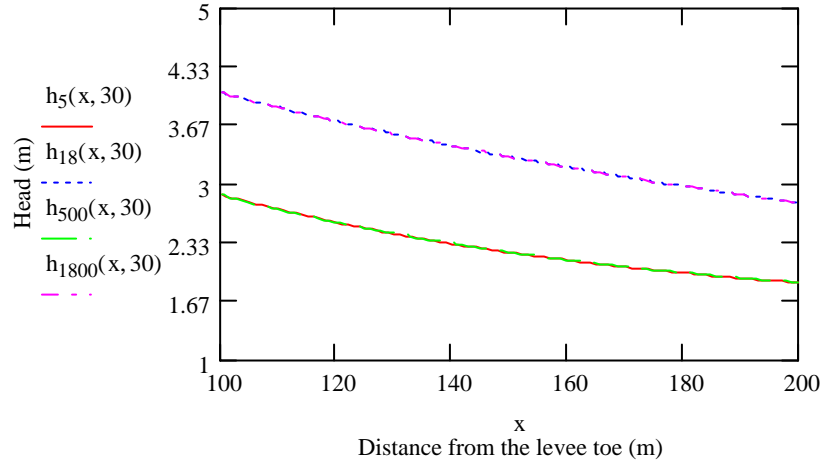
$$h_1 := 1.5 \text{ meter}$$

$$h_{1800}(x, t) := \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ -\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \right] \\ + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \left[ \exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \dots \right. \right. \\ \left. \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \right. \\ \left. + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[ \cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \dots \right. \right. \\ \left. \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \right] \\ + \frac{1}{2} \cdot h_0 \cdot \left( \exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \text{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S}} \cdot t\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \text{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S}} \cdot t\right) \right)$$

**Figure 7.10**

$t := 30$  day

$x := 100..200$  m



$$h_5(100, 30) = 2.872$$

$$h_{18}(100, 30) = 4.031$$

$$h_{500}(100, 30) = 2.875$$

$$h_{1800}(100, 30) = 4.032$$

$$h_5(200, 30) = 1.872$$

$$h_{18}(200, 30) = 2.781$$

$$h_{500}(200, 30) = 1.878$$

$$h_{1800}(200, 30) = 2.782$$

$z := 5$  m

$$i_5(x, t) := \frac{1}{z} \cdot h_5(x, t)$$

$$i_{18}(x, t) := \frac{1}{z} \cdot h_{18}(x, t)$$

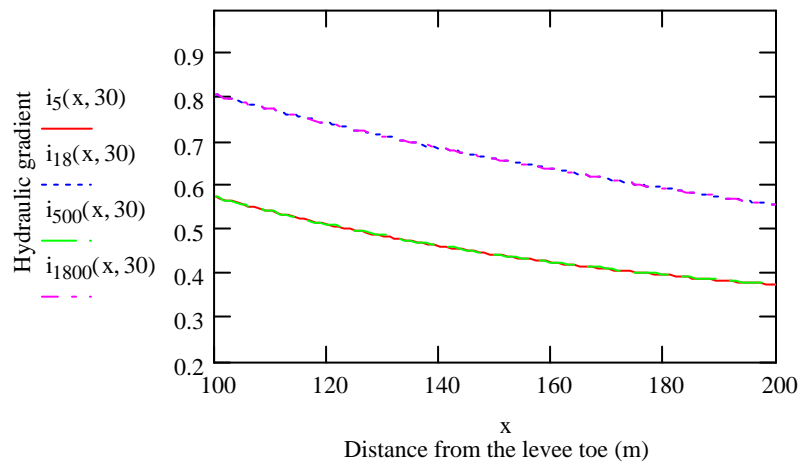
$$i_{500}(x, t) := \frac{1}{z} \cdot h_{500}(x, t)$$

$$i_{1800}(x, t) := \frac{1}{z} \cdot h_{1800}(x, t)$$

**Figure 7.11**

$t := 30$

$x := 100..200$



$$i_5(100, 30) = 0.574$$

$$i_{18}(100, 30) = 0.806$$

$$i_{500}(100, 30) = 0.575$$

$$i_{1800}(100, 30) = 0.806$$

$$i_5(200, 30) = 0.374$$

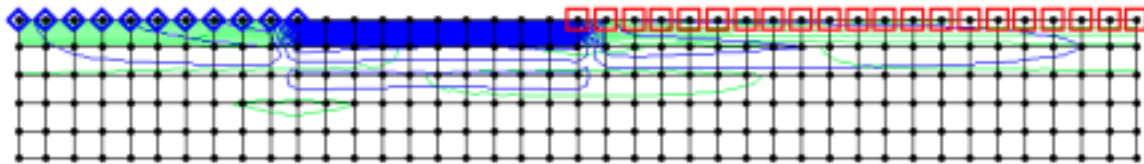
$$i_{18}(200, 30) = 0.556$$

$$i_{500}(200, 30) = 0.376$$

$$i_{1800}(200, 30) = 0.556$$

**Figure 7.12****SEEP2D Model**

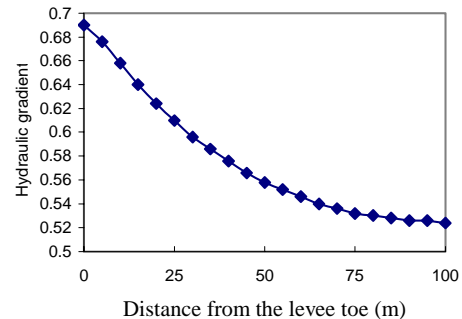
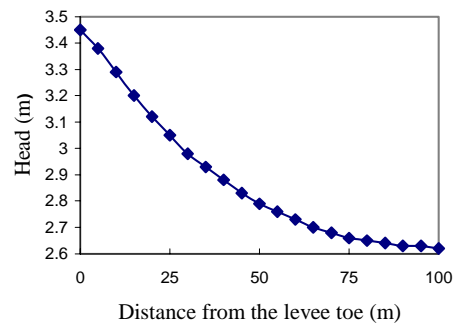
An unconfined aquifer with a depth of 25 m, and hydraulic conductivities of  $k_h=0.1$  cm/sec,  $k_v=0.0001$  cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head boundary was defined at riverside and exit face boundary was defined at landside of the levee. The figure of the model is below:



For cumulative analysis

25m exit face,  $T=0.025$  m<sup>2</sup>/sec

Node	Distance (m)	Head (m)	Head-25 (m)	$i=h/z$
122	0	28.45	3.45	0.69
128	5	28.38	3.38	0.676
134	10	28.29	3.29	0.658
140	15	28.2	3.2	0.64
146	20	28.12	3.12	0.624
152	25	28.05	3.05	0.61
158	30	27.98	2.98	0.596
164	35	27.93	2.93	0.586
170	40	27.88	2.88	0.576
176	45	27.83	2.83	0.566
182	50	27.79	2.79	0.558
188	55	27.76	2.76	0.552
194	60	27.73	2.73	0.546
200	65	27.7	2.7	0.54
206	70	27.68	2.68	0.536
212	75	27.66	2.66	0.532
218	80	27.65	2.65	0.53
224	85	27.64	2.64	0.528
230	90	27.63	2.63	0.526
236	95	27.63	2.63	0.526
242	100	27.62	2.62	0.524



Note: Node numbers 122 to 242 are located at 5 m below the landside of the levee.

**Model Output**

Plane flow problem

25m exit face,  $T=0.025$  m<sup>2</sup>/sec

Number of nodal points----- 246

Number of elements----- 200

Number of diff. materials--- 1

Elevation of datum----- 0.000

Unsaturated flow option----- 0

Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information									
Node	BC	X	Y	Flow-head					
1	1	0.00	25.00	31.50	66	0	50.00	0.00	0.00
2	0	0.00	20.00	0.00	67	0	55.00	25.00	0.00
3	0	0.00	15.00	0.00	68	0	55.00	20.00	0.00
4	0	0.00	10.00	0.00	69	0	55.00	15.00	0.00
5	0	0.00	5.00	0.00	70	0	55.00	10.00	0.00
6	0	0.00	0.00	0.00	71	0	55.00	5.00	0.00
7	1	5.00	25.00	31.50	72	0	55.00	0.00	0.00
8	0	5.00	20.00	0.00	73	0	60.00	25.00	0.00
9	0	5.00	15.00	0.00	74	0	60.00	20.00	0.00
10	0	5.00	10.00	0.00	75	0	60.00	15.00	0.00
11	0	5.00	5.00	0.00	76	0	60.00	10.00	0.00
12	0	5.00	0.00	0.00	77	0	60.00	5.00	0.00
13	1	10.00	25.00	31.50	78	0	60.00	0.00	0.00
14	0	10.00	20.00	0.00	79	0	65.00	25.00	0.00
15	0	10.00	15.00	0.00	80	0	65.00	20.00	0.00
16	0	10.00	10.00	0.00	81	0	65.00	15.00	0.00
17	0	10.00	5.00	0.00	82	0	65.00	10.00	0.00
18	0	10.00	0.00	0.00	83	0	65.00	5.00	0.00
19	1	15.00	25.00	31.50	84	0	65.00	0.00	0.00
20	0	15.00	20.00	0.00	85	0	70.00	25.00	0.00
21	0	15.00	15.00	0.00	86	0	70.00	20.00	0.00
22	0	15.00	10.00	0.00	87	0	70.00	15.00	0.00
23	0	15.00	5.00	0.00	88	0	70.00	10.00	0.00
24	0	15.00	0.00	0.00	89	0	70.00	5.00	0.00
25	1	20.00	25.00	31.50	90	0	70.00	0.00	0.00
26	0	20.00	20.00	0.00	91	0	75.00	25.00	0.00
27	0	20.00	15.00	0.00	92	0	75.00	20.00	0.00
28	0	20.00	10.00	0.00	93	0	75.00	15.00	0.00
29	0	20.00	5.00	0.00	94	0	75.00	10.00	0.00
30	0	20.00	0.00	0.00	95	0	75.00	5.00	0.00
31	1	25.00	25.00	31.50	96	0	75.00	0.00	0.00
32	0	25.00	20.00	0.00	97	0	80.00	25.00	0.00
33	0	25.00	15.00	0.00	98	0	80.00	20.00	0.00
34	0	25.00	10.00	0.00	99	0	80.00	15.00	0.00
35	0	25.00	5.00	0.00	100	0	80.00	10.00	0.00
36	0	25.00	0.00	0.00	101	0	80.00	5.00	0.00
37	1	30.00	25.00	31.50	102	0	80.00	0.00	0.00
38	0	30.00	20.00	0.00	103	0	85.00	25.00	0.00
39	0	30.00	15.00	0.00	104	0	85.00	20.00	0.00
40	0	30.00	10.00	0.00	105	0	85.00	15.00	0.00
41	0	30.00	5.00	0.00	106	0	85.00	10.00	0.00
42	0	30.00	0.00	0.00	107	0	85.00	5.00	0.00
43	1	35.00	25.00	31.50	108	0	85.00	0.00	0.00
44	0	35.00	20.00	0.00	109	0	90.00	25.00	0.00
45	0	35.00	15.00	0.00	110	0	90.00	20.00	0.00
46	0	35.00	10.00	0.00	111	0	90.00	15.00	0.00
47	0	35.00	5.00	0.00	112	0	90.00	10.00	0.00
48	0	35.00	0.00	0.00	113	0	90.00	5.00	0.00
49	1	40.00	25.00	31.50	114	0	90.00	0.00	0.00
50	0	40.00	20.00	0.00	115	0	95.00	25.00	0.00
51	0	40.00	15.00	0.00	116	0	95.00	20.00	0.00
52	0	40.00	10.00	0.00	117	0	95.00	15.00	0.00
53	0	40.00	5.00	0.00	118	0	95.00	10.00	0.00
54	0	40.00	0.00	0.00	119	0	95.00	5.00	0.00
55	1	45.00	25.00	31.50	120	0	95.00	0.00	0.00
56	0	45.00	20.00	0.00	121	2	100.00	25.00	0.00
57	0	45.00	15.00	0.00	122	0	100.00	20.00	0.00
58	0	45.00	10.00	0.00	123	0	100.00	15.00	0.00
59	0	45.00	5.00	0.00	124	0	100.00	10.00	0.00
60	0	45.00	0.00	0.00	125	0	100.00	5.00	0.00
61	1	50.00	25.00	31.50	126	0	100.00	0.00	0.00
62	0	50.00	20.00	0.00	127	2	105.00	25.00	0.00
63	0	50.00	15.00	0.00	128	0	105.00	20.00	0.00
64	0	50.00	10.00	0.00	129	0	105.00	15.00	0.00
65	0	50.00	5.00	0.00	130	0	105.00	10.00	0.00
					131	0	105.00	5.00	0.00
					132	0	105.00	0.00	0.00
					133	2	110.00	25.00	0.00
					134	0	110.00	20.00	0.00
					135	0	110.00	15.00	0.00

136	0	110.00	10.00	0.00
137	0	110.00	5.00	0.00
138	0	110.00	0.00	0.00
139	2	115.00	25.00	0.00
140	0	115.00	20.00	0.00
141	0	115.00	15.00	0.00
142	0	115.00	10.00	0.00
143	0	115.00	5.00	0.00
144	0	115.00	0.00	0.00
145	2	120.00	25.00	0.00
146	0	120.00	20.00	0.00
147	0	120.00	15.00	0.00
148	0	120.00	10.00	0.00
149	0	120.00	5.00	0.00
150	0	120.00	0.00	0.00
151	2	125.00	25.00	0.00
152	0	125.00	20.00	0.00
153	0	125.00	15.00	0.00
154	0	125.00	10.00	0.00
155	0	125.00	5.00	0.00
156	0	125.00	0.00	0.00
157	2	130.00	25.00	0.00
158	0	130.00	20.00	0.00
159	0	130.00	15.00	0.00
160	0	130.00	10.00	0.00
161	0	130.00	5.00	0.00
162	0	130.00	0.00	0.00
163	2	135.00	25.00	0.00
164	0	135.00	20.00	0.00
165	0	135.00	15.00	0.00
166	0	135.00	10.00	0.00
167	0	135.00	5.00	0.00
168	0	135.00	0.00	0.00
169	2	140.00	25.00	0.00
170	0	140.00	20.00	0.00
171	0	140.00	15.00	0.00
172	0	140.00	10.00	0.00
173	0	140.00	5.00	0.00
174	0	140.00	0.00	0.00
175	2	145.00	25.00	0.00
176	0	145.00	20.00	0.00
177	0	145.00	15.00	0.00
178	0	145.00	10.00	0.00
179	0	145.00	5.00	0.00
180	0	145.00	0.00	0.00
181	2	150.00	25.00	0.00
182	0	150.00	20.00	0.00
183	0	150.00	15.00	0.00
184	0	150.00	10.00	0.00
185	0	150.00	5.00	0.00
186	0	150.00	0.00	0.00
187	2	155.00	25.00	0.00
188	0	155.00	20.00	0.00
189	0	155.00	15.00	0.00
190	0	155.00	10.00	0.00
191	0	155.00	5.00	0.00

192	0	155.00	0.00	0.00
193	2	160.00	25.00	0.00
194	0	160.00	20.00	0.00
195	0	160.00	15.00	0.00
196	0	160.00	10.00	0.00
197	0	160.00	5.00	0.00
198	0	160.00	0.00	0.00
199	2	165.00	25.00	0.00
200	0	165.00	20.00	0.00
201	0	165.00	15.00	0.00
202	0	165.00	10.00	0.00
203	0	165.00	5.00	0.00
204	0	165.00	0.00	0.00
205	2	170.00	25.00	0.00
206	0	170.00	20.00	0.00
207	0	170.00	15.00	0.00
208	0	170.00	10.00	0.00
209	0	170.00	5.00	0.00
210	0	170.00	0.00	0.00
211	2	175.00	25.00	0.00
212	0	175.00	20.00	0.00
213	0	175.00	15.00	0.00
214	0	175.00	10.00	0.00
215	0	175.00	5.00	0.00
216	0	175.00	0.00	0.00
217	2	180.00	25.00	0.00
218	0	180.00	20.00	0.00
219	0	180.00	15.00	0.00
220	0	180.00	10.00	0.00
221	0	180.00	5.00	0.00
222	0	180.00	0.00	0.00
223	2	185.00	25.00	0.00
224	0	185.00	20.00	0.00
225	0	185.00	15.00	0.00
226	0	185.00	10.00	0.00
227	0	185.00	5.00	0.00
228	0	185.00	0.00	0.00
229	2	190.00	25.00	0.00
230	0	190.00	20.00	0.00
231	0	190.00	15.00	0.00
232	0	190.00	10.00	0.00
233	0	190.00	5.00	0.00
234	0	190.00	0.00	0.00
235	2	195.00	25.00	0.00
236	0	195.00	20.00	0.00
237	0	195.00	15.00	0.00
238	0	195.00	10.00	0.00
239	0	195.00	5.00	0.00
240	0	195.00	0.00	0.00
241	2	200.00	25.00	0.00
242	0	200.00	20.00	0.00
243	0	200.00	15.00	0.00
244	0	200.00	10.00	0.00
245	0	200.00	5.00	0.00
246	0	200.00	0.00	0.00

# Nodal Flows and Heads

Node	Head	Percentage of available head	Flow			
1	0.3150E+02	100.0 %	0.2029E+00	65	0.2786E+02	44.0 %
2	0.2779E+02	43.0 %		66	0.2785E+02	43.9 %
3	0.2785E+02	43.8 %		67	0.3083E+02	89.6 %
4	0.2786E+02	44.0 %		68	0.2759E+02	39.9 %
5	0.2785E+02	43.9 %		69	0.2792E+02	44.9 %
6	0.2785E+02	43.9 %		70	0.2784E+02	43.7 %
7	0.3150E+02	100.0 %	0.4062E+00	71	0.2786E+02	44.0 %
8	0.2779E+02	42.9 %		72	0.2785E+02	43.9 %
9	0.2785E+02	43.8 %		73	0.3017E+02	79.5 %
10	0.2786E+02	44.0 %		74	0.2770E+02	41.5 %
11	0.2785E+02	43.9 %		75	0.2789E+02	44.5 %
12	0.2785E+02	43.9 %		76	0.2784E+02	43.7 %
13	0.3150E+02	100.0 %	0.4076E+00	77	0.2786E+02	43.9 %
14	0.2778E+02	42.8 %		78	0.2785E+02	43.9 %
15	0.2785E+02	43.9 %		79	0.2952E+02	69.5 %
16	0.2786E+02	44.0 %		80	0.2779E+02	42.9 %
17	0.2785E+02	43.9 %		81	0.2787E+02	44.2 %
18	0.2785E+02	43.9 %		82	0.2785E+02	43.8 %
19	0.3150E+02	100.0 %	0.4098E+00	83	0.2786E+02	43.9 %
20	0.2777E+02	42.6 %		84	0.2785E+02	43.9 %
21	0.2786E+02	43.9 %		85	0.2887E+02	59.6 %
22	0.2786E+02	43.9 %		86	0.2788E+02	44.3 %
23	0.2785E+02	43.9 %		87	0.2785E+02	43.9 %
24	0.2785E+02	43.9 %		88	0.2785E+02	43.9 %
25	0.3150E+02	100.0 %	0.4130E+00	89	0.2785E+02	43.9 %
26	0.2775E+02	42.2 %		90	0.2785E+02	43.9 %
27	0.2786E+02	44.0 %		91	0.2824E+02	49.8 %
28	0.2785E+02	43.9 %		92	0.2797E+02	45.7 %
29	0.2785E+02	43.9 %		93	0.2784E+02	43.6 %
30	0.2785E+02	43.9 %		94	0.2786E+02	43.9 %
31	0.3150E+02	100.0 %	0.4172E+00	95	0.2785E+02	43.9 %
32	0.2772E+02	41.8 %		96	0.2785E+02	43.9 %
33	0.2787E+02	44.1 %		97	0.2760E+02	40.0 %
34	0.2785E+02	43.9 %		98	0.2806E+02	47.0 %
35	0.2785E+02	43.9 %		99	0.2782E+02	43.3 %
36	0.2785E+02	43.9 %		100	0.2786E+02	44.0 %
37	0.3150E+02	100.0 %	0.4223E+00	101	0.2785E+02	43.9 %
38	0.2768E+02	41.3 %		102	0.2785E+02	43.9 %
39	0.2788E+02	44.3 %		103	0.2696E+02	30.2 %
40	0.2785E+02	43.8 %		104	0.2815E+02	48.4 %
41	0.2785E+02	43.9 %		105	0.2780E+02	43.1 %
42	0.2785E+02	43.9 %		106	0.2786E+02	44.1 %
43	0.3150E+02	100.0 %	0.4284E+00	107	0.2785E+02	43.9 %
44	0.2764E+02	40.7 %		108	0.2785E+02	43.9 %
45	0.2789E+02	44.5 %		109	0.2632E+02	20.3 %
46	0.2785E+02	43.8 %		110	0.2824E+02	49.8 %
47	0.2786E+02	43.9 %		111	0.2778E+02	42.7 %
48	0.2785E+02	43.9 %		112	0.2787E+02	44.1 %
49	0.3150E+02	100.0 %	0.4355E+00	113	0.2785E+02	43.8 %
50	0.2760E+02	39.9 %		114	0.2785E+02	43.9 %
51	0.2791E+02	44.7 %		115	0.2567E+02	10.2 %
52	0.2784E+02	43.7 %		116	0.2834E+02	51.4 %
53	0.2786E+02	43.9 %		117	0.2775E+02	42.4 %
54	0.2785E+02	43.9 %		118	0.2787E+02	44.2 %
55	0.3150E+02	100.0 %	0.4436E+00	119	0.2785E+02	43.8 %
56	0.2754E+02	39.1 %		120	0.2786E+02	43.9 %
57	0.2792E+02	45.0 %		121	0.2500E+02	0.0 %
58	0.2784E+02	43.7 %		122	0.2845E+02	53.0 %
59	0.2786E+02	44.0 %		123	0.2773E+02	41.9 %
60	0.2785E+02	43.9 %		124	0.2788E+02	44.3 %
61	0.3150E+02	100.0 %	0.1727E+02	125	0.2785E+02	43.8 %
62	0.2748E+02	38.2 %		126	0.2786E+02	43.9 %
63	0.2794E+02	45.3 %		127	0.2500E+02	0.0 %
64	0.2783E+02	43.6 %		128	0.2838E+02	52.1 %
				129	0.2774E+02	42.2 %
				130	0.2788E+02	44.3 %
				131	0.2785E+02	43.8 %
				132	0.2786E+02	43.9 %
				133	0.2516E+02	2.4 %
						-0.1698E+02
						-0.4273E+01
						-0.5684E-13

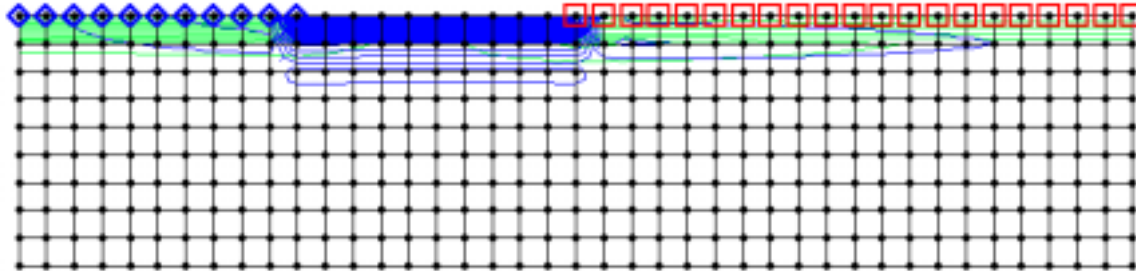
134	0.2829E+02	50.5 %		197	0.2785E+02	43.9 %	
135	0.2777E+02	42.6 %		198	0.2785E+02	43.9 %	
136	0.2787E+02	44.2 %		199	0.2613E+02	17.3 %	0.1705E-12
137	0.2785E+02	43.8 %		200	0.2770E+02	41.6 %	
138	0.2786E+02	43.9 %		201	0.2788E+02	44.4 %	
139	0.2530E+02	4.6 %	0.1705E-12	202	0.2785E+02	43.8 %	
140	0.2820E+02	49.2 %		203	0.2785E+02	43.9 %	
141	0.2779E+02	42.9 %		204	0.2785E+02	43.9 %	
142	0.2787E+02	44.1 %		205	0.2616E+02	17.9 %	-0.1705E-12
143	0.2785E+02	43.9 %		206	0.2768E+02	41.3 %	
144	0.2785E+02	43.9 %		207	0.2789E+02	44.4 %	
145	0.2543E+02	6.5 %	0.3979E-12	208	0.2785E+02	43.8 %	
146	0.2812E+02	48.0 %		209	0.2785E+02	43.9 %	
147	0.2781E+02	43.2 %		210	0.2785E+02	43.9 %	
148	0.2786E+02	44.0 %		211	0.2620E+02	18.4 %	0.0000E+00
149	0.2785E+02	43.9 %		212	0.2766E+02	41.0 %	
150	0.2785E+02	43.9 %		213	0.2789E+02	44.4 %	
151	0.2554E+02	8.3 %	-0.5684E-13	214	0.2785E+02	43.8 %	
152	0.2805E+02	46.9 %		215	0.2785E+02	43.9 %	
153	0.2782E+02	43.4 %		216	0.2785E+02	43.9 %	
154	0.2786E+02	44.0 %		217	0.2622E+02	18.8 %	0.1137E-12
155	0.2785E+02	43.9 %		218	0.2765E+02	40.8 %	
156	0.2785E+02	43.9 %		219	0.2789E+02	44.5 %	
157	0.2565E+02	10.0 %	-0.5684E-13	220	0.2785E+02	43.8 %	
158	0.2798E+02	45.9 %		221	0.2785E+02	43.9 %	
159	0.2784E+02	43.7 %		222	0.2785E+02	43.9 %	
160	0.2785E+02	43.9 %		223	0.2624E+02	19.1 %	-0.5684E-13
161	0.2785E+02	43.9 %		224	0.2764E+02	40.6 %	
162	0.2785E+02	43.9 %		225	0.2789E+02	44.5 %	
163	0.2574E+02	11.4 %	-0.5684E-13	226	0.2785E+02	43.8 %	
164	0.2793E+02	45.0 %		227	0.2785E+02	43.9 %	
165	0.2785E+02	43.8 %		228	0.2785E+02	43.9 %	
166	0.2785E+02	43.9 %		229	0.2626E+02	19.3 %	-0.5684E-13
167	0.2785E+02	43.9 %		230	0.2763E+02	40.5 %	
168	0.2785E+02	43.9 %		231	0.2789E+02	44.5 %	
169	0.2583E+02	12.7 %	0.1137E-12	232	0.2785E+02	43.8 %	
170	0.2788E+02	44.3 %		233	0.2785E+02	43.9 %	
171	0.2786E+02	44.0 %		234	0.2785E+02	43.9 %	
172	0.2785E+02	43.9 %		235	0.2627E+02	19.5 %	0.5116E-12
173	0.2785E+02	43.9 %		236	0.2763E+02	40.4 %	
174	0.2785E+02	43.9 %		237	0.2789E+02	44.5 %	
175	0.2590E+02	13.9 %	0.4547E-12	238	0.2785E+02	43.8 %	
176	0.2783E+02	43.6 %		239	0.2785E+02	43.9 %	
177	0.2787E+02	44.1 %		240	0.2785E+02	43.9 %	
178	0.2785E+02	43.8 %		241	0.2627E+02	19.5 %	-0.1705E-12
179	0.2785E+02	43.9 %		242	0.2762E+02	40.4 %	
180	0.2785E+02	43.9 %		243	0.2789E+02	44.5 %	
181	0.2597E+02	14.9 %	-0.1137E-12	244	0.2785E+02	43.8 %	
182	0.2779E+02	43.0 %		245	0.2785E+02	43.9 %	
183	0.2787E+02	44.2 %		246	0.2785E+02	43.9 %	
184	0.2785E+02	43.8 %					
185	0.2785E+02	43.9 %					
186	0.2785E+02	43.9 %					
187	0.2603E+02	15.8 %	0.5684E-13				
188	0.2776E+02	42.4 %					
189	0.2788E+02	44.3 %					
190	0.2785E+02	43.8 %					
191	0.2785E+02	43.9 %					
192	0.2785E+02	43.9 %					
193	0.2608E+02	16.6 %	0.0000E+00				
194	0.2773E+02	42.0 %					
195	0.2788E+02	44.3 %					
196	0.2785E+02	43.8 %					

Flow = 2.1252E+01



**Figure 7.13**  
**SEEP2D Model**

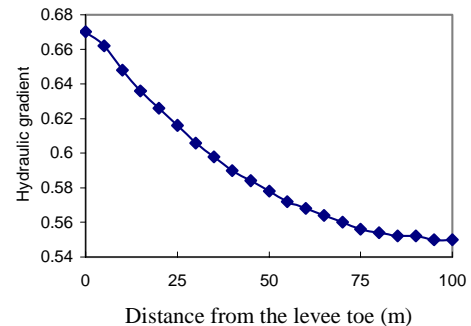
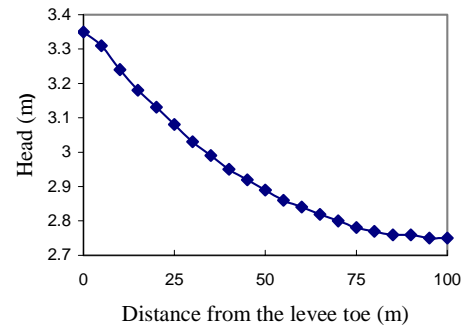
An unconfined aquifer with a depth of 45 m, and hydraulic conductivities of  $k_h=0.2$  cm/sec,  $k_v=0.0001$  cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head boundary was defined at riverside and exit face boundary was defined at landside of the levee. The figure is below:



For cumulative analysis  
45m exit face,  $T=0.09$  m<sup>2</sup>/sec

Node	Distance (m)	Head (m)	Head-45 (m)	$i=h/z$
202	0	48.35	3.35	0.67
212	5	48.31	3.31	0.662
222	10	48.24	3.24	0.648
232	15	48.18	3.18	0.636
242	20	48.13	3.13	0.626
252	25	48.08	3.08	0.616
262	30	48.03	3.03	0.606
272	35	47.99	2.99	0.598
282	40	47.95	2.95	0.59
292	45	47.92	2.92	0.584
302	50	47.89	2.89	0.578
312	55	47.86	2.86	0.572
322	60	47.84	2.84	0.568
332	65	47.82	2.82	0.564
342	70	47.8	2.8	0.56
352	75	47.78	2.78	0.556
362	80	47.77	2.77	0.554
372	85	47.76	2.76	0.552
382	90	47.76	2.76	0.552
392	95	47.75	2.75	0.55
402	100	47.75	2.75	0.55

Flow = 38.272



Note: Node numbers 202 to 402 are located at 5 m below the landside of the levee.

### Model Output

Plane flow problem  
45m exit face,  $T=0.09$  m<sup>2</sup>/sec  
Number of nodal points----- 410  
Number of elements----- 360  
Number of diff. materials--- 1  
Elevation of datum----- 0.000  
Unsaturated flow option----- 0  
Material Properties  
Mat K1 K2 Angle Uspar1 Uspar2  
1 0.1728E+03 0.8600E-01 0.0000E+00 0.1000E-02 0.0000E+00

Node Point Information				
Node	BC	X	Y	Flow-head
1	1	0.00	45.00	51.50
2	0	0.00	40.00	0.00
3	0	0.00	35.00	0.00
4	0	0.00	30.00	0.00
5	0	0.00	25.00	0.00
6	0	0.00	20.00	0.00
7	0	0.00	15.00	0.00
8	0	0.00	10.00	0.00
9	0	0.00	5.00	0.00
10	0	0.00	0.00	0.00
11	1	5.00	45.00	51.50
12	0	5.00	40.00	0.00
13	0	5.00	35.00	0.00
14	0	5.00	30.00	0.00
15	0	5.00	25.00	0.00
16	0	5.00	20.00	0.00
17	0	5.00	15.00	0.00
18	0	5.00	10.00	0.00
19	0	5.00	5.00	0.00
20	0	5.00	0.00	0.00
21	1	10.00	45.00	51.50
22	0	10.00	40.00	0.00
23	0	10.00	35.00	0.00
24	0	10.00	30.00	0.00
25	0	10.00	25.00	0.00
26	0	10.00	20.00	0.00
27	0	10.00	15.00	0.00
28	0	10.00	10.00	0.00
29	0	10.00	5.00	0.00
30	0	10.00	0.00	0.00
31	1	15.00	45.00	51.50
32	0	15.00	40.00	0.00
33	0	15.00	35.00	0.00
34	0	15.00	30.00	0.00
35	0	15.00	25.00	0.00
36	0	15.00	20.00	0.00
37	0	15.00	15.00	0.00
38	0	15.00	10.00	0.00
39	0	15.00	5.00	0.00
40	0	15.00	0.00	0.00
41	1	20.00	45.00	51.50
42	0	20.00	40.00	0.00
43	0	20.00	35.00	0.00
44	0	20.00	30.00	0.00
45	0	20.00	25.00	0.00
46	0	20.00	20.00	0.00
47	0	20.00	15.00	0.00
48	0	20.00	10.00	0.00
49	0	20.00	5.00	0.00
50	0	20.00	0.00	0.00
51	1	25.00	45.00	51.50
52	0	25.00	40.00	0.00
53	0	25.00	35.00	0.00
54	0	25.00	30.00	0.00
55	0	25.00	25.00	0.00
56	0	25.00	20.00	0.00
57	0	25.00	15.00	0.00
58	0	25.00	10.00	0.00
59	0	25.00	5.00	0.00
60	0	25.00	0.00	0.00
61	1	30.00	45.00	51.50
62	0	30.00	40.00	0.00
63	0	30.00	35.00	0.00
64	0	30.00	30.00	0.00

65	0	30.00	25.00	0.00
66	0	30.00	20.00	0.00
67	0	30.00	15.00	0.00
68	0	30.00	10.00	0.00
69	0	30.00	5.00	0.00
70	0	30.00	0.00	0.00
71	1	35.00	45.00	51.50
72	0	35.00	40.00	0.00
73	0	35.00	35.00	0.00
74	0	35.00	30.00	0.00
75	0	35.00	25.00	0.00
76	0	35.00	20.00	0.00
77	0	35.00	15.00	0.00
78	0	35.00	10.00	0.00
79	0	35.00	5.00	0.00
80	0	35.00	0.00	0.00
81	1	40.00	45.00	51.50
82	0	40.00	40.00	0.00
83	0	40.00	35.00	0.00
84	0	40.00	30.00	0.00
85	0	40.00	25.00	0.00
86	0	40.00	20.00	0.00
87	0	40.00	15.00	0.00
88	0	40.00	10.00	0.00
89	0	40.00	5.00	0.00
90	0	40.00	0.00	0.00
91	1	45.00	45.00	51.50
92	0	45.00	40.00	0.00
93	0	45.00	35.00	0.00
94	0	45.00	30.00	0.00
95	0	45.00	25.00	0.00
96	0	45.00	20.00	0.00
97	0	45.00	15.00	0.00
98	0	45.00	10.00	0.00
99	0	45.00	5.00	0.00
100	0	45.00	0.00	0.00
101	1	50.00	45.00	51.50
102	0	50.00	40.00	0.00
103	0	50.00	35.00	0.00
104	0	50.00	30.00	0.00
105	0	50.00	25.00	0.00
106	0	50.00	20.00	0.00
107	0	50.00	15.00	0.00
108	0	50.00	10.00	0.00
109	0	50.00	5.00	0.00
110	0	50.00	0.00	0.00
111	0	55.00	45.00	0.00
112	0	55.00	40.00	0.00
113	0	55.00	35.00	0.00
114	0	55.00	30.00	0.00
115	0	55.00	25.00	0.00
116	0	55.00	20.00	0.00
117	0	55.00	15.00	0.00
118	0	55.00	10.00	0.00
119	0	55.00	5.00	0.00
120	0	55.00	0.00	0.00
121	0	60.00	45.00	0.00
122	0	60.00	40.00	0.00
123	0	60.00	35.00	0.00
124	0	60.00	30.00	0.00
125	0	60.00	25.00	0.00
126	0	60.00	20.00	0.00
127	0	60.00	15.00	0.00
128	0	60.00	10.00	0.00
129	0	60.00	5.00	0.00
130	0	60.00	0.00	0.00
131	0	65.00	45.00	0.00
132	0	65.00	40.00	0.00

133	0	65.00	35.00	0.00
134	0	65.00	30.00	0.00
135	0	65.00	25.00	0.00
136	0	65.00	20.00	0.00
137	0	65.00	15.00	0.00
138	0	65.00	10.00	0.00
139	0	65.00	5.00	0.00
140	0	65.00	0.00	0.00
141	0	70.00	45.00	0.00
142	0	70.00	40.00	0.00
143	0	70.00	35.00	0.00
144	0	70.00	30.00	0.00
145	0	70.00	25.00	0.00
146	0	70.00	20.00	0.00
147	0	70.00	15.00	0.00
148	0	70.00	10.00	0.00
149	0	70.00	5.00	0.00
150	0	70.00	0.00	0.00
151	0	75.00	45.00	0.00
152	0	75.00	40.00	0.00
153	0	75.00	35.00	0.00
154	0	75.00	30.00	0.00
155	0	75.00	25.00	0.00
156	0	75.00	20.00	0.00
157	0	75.00	15.00	0.00
158	0	75.00	10.00	0.00
159	0	75.00	5.00	0.00
160	0	75.00	0.00	0.00
161	0	80.00	45.00	0.00
162	0	80.00	40.00	0.00
163	0	80.00	35.00	0.00
164	0	80.00	30.00	0.00
165	0	80.00	25.00	0.00
166	0	80.00	20.00	0.00
167	0	80.00	15.00	0.00
168	0	80.00	10.00	0.00
169	0	80.00	5.00	0.00
170	0	80.00	0.00	0.00
171	0	85.00	45.00	0.00
172	0	85.00	40.00	0.00
173	0	85.00	35.00	0.00
174	0	85.00	30.00	0.00
175	0	85.00	25.00	0.00
176	0	85.00	20.00	0.00
177	0	85.00	15.00	0.00
178	0	85.00	10.00	0.00
179	0	85.00	5.00	0.00
180	0	85.00	0.00	0.00
181	0	90.00	45.00	0.00
182	0	90.00	40.00	0.00
183	0	90.00	35.00	0.00
184	0	90.00	30.00	0.00
185	0	90.00	25.00	0.00
186	0	90.00	20.00	0.00
187	0	90.00	15.00	0.00
188	0	90.00	10.00	0.00
189	0	90.00	5.00	0.00
190	0	90.00	0.00	0.00
191	0	95.00	45.00	0.00
192	0	95.00	40.00	0.00
193	0	95.00	35.00	0.00
194	0	95.00	30.00	0.00
195	0	95.00	25.00	0.00
196	0	95.00	20.00	0.00
197	0	95.00	15.00	0.00
198	0	95.00	10.00	0.00
199	0	95.00	5.00	0.00
200	0	95.00	0.00	0.00
201	2	100.00	45.00	0.00
202	0	100.00	40.00	0.00

203	0	100.00	35.00	0.00
204	0	100.00	30.00	0.00
205	0	100.00	25.00	0.00
206	0	100.00	20.00	0.00
207	0	100.00	15.00	0.00
208	0	100.00	10.00	0.00
209	0	100.00	5.00	0.00
210	0	100.00	0.00	0.00
211	2	105.00	45.00	0.00
212	0	105.00	40.00	0.00
213	0	105.00	35.00	0.00
214	0	105.00	30.00	0.00
215	0	105.00	25.00	0.00
216	0	105.00	20.00	0.00
217	0	105.00	15.00	0.00
218	0	105.00	10.00	0.00
219	0	105.00	5.00	0.00
220	0	105.00	0.00	0.00
221	2	110.00	45.00	0.00
222	0	110.00	40.00	0.00
223	0	110.00	35.00	0.00
224	0	110.00	30.00	0.00
225	0	110.00	25.00	0.00
226	0	110.00	20.00	0.00
227	0	110.00	15.00	0.00
228	0	110.00	10.00	0.00
229	0	110.00	5.00	0.00
230	0	110.00	0.00	0.00
231	2	115.00	45.00	0.00
232	0	115.00	40.00	0.00
233	0	115.00	35.00	0.00
234	0	115.00	30.00	0.00
235	0	115.00	25.00	0.00
236	0	115.00	20.00	0.00
237	0	115.00	15.00	0.00
238	0	115.00	10.00	0.00
239	0	115.00	5.00	0.00
240	0	115.00	0.00	0.00
241	2	120.00	45.00	0.00
242	0	120.00	40.00	0.00
243	0	120.00	35.00	0.00
244	0	120.00	30.00	0.00
245	0	120.00	25.00	0.00
246	0	120.00	20.00	0.00
247	0	120.00	15.00	0.00
248	0	120.00	10.00	0.00
249	0	120.00	5.00	0.00
250	0	120.00	0.00	0.00
251	2	125.00	45.00	0.00
252	0	125.00	40.00	0.00
253	0	125.00	35.00	0.00
254	0	125.00	30.00	0.00
255	0	125.00	25.00	0.00
256	0	125.00	20.00	0.00
257	0	125.00	15.00	0.00
258	0	125.00	10.00	0.00
259	0	125.00	5.00	0.00
260	0	125.00	0.00	0.00
261	2	130.00	45.00	0.00
262	0	130.00	40.00	0.00
263	0	130.00	35.00	0.00
264	0	130.00	30.00	0.00
265	0	130.00	25.00	0.00
266	0	130.00	20.00	0.00
267	0	130.00	15.00	0.00
268	0	130.00	10.00	0.00
269	0	130.00	5.00	0.00
270	0	130.00	0.00	0.00
271	2	135.00	45.00	0.00
272	0	135.00	40.00	0.00

273	0	135.00	35.00	0.00
274	0	135.00	30.00	0.00
275	0	135.00	25.00	0.00
276	0	135.00	20.00	0.00
277	0	135.00	15.00	0.00
278	0	135.00	10.00	0.00
279	0	135.00	5.00	0.00
280	0	135.00	0.00	0.00
281	2	140.00	45.00	0.00
282	0	140.00	40.00	0.00
283	0	140.00	35.00	0.00
284	0	140.00	30.00	0.00
285	0	140.00	25.00	0.00
286	0	140.00	20.00	0.00
287	0	140.00	15.00	0.00
288	0	140.00	10.00	0.00
289	0	140.00	5.00	0.00
290	0	140.00	0.00	0.00
291	2	145.00	45.00	0.00
292	0	145.00	40.00	0.00
293	0	145.00	35.00	0.00
294	0	145.00	30.00	0.00
295	0	145.00	25.00	0.00
296	0	145.00	20.00	0.00
297	0	145.00	15.00	0.00
298	0	145.00	10.00	0.00
299	0	145.00	5.00	0.00
300	0	145.00	0.00	0.00
301	2	150.00	45.00	0.00
302	0	150.00	40.00	0.00
303	0	150.00	35.00	0.00
304	0	150.00	30.00	0.00
305	0	150.00	25.00	0.00
306	0	150.00	20.00	0.00
307	0	150.00	15.00	0.00
308	0	150.00	10.00	0.00
309	0	150.00	5.00	0.00
310	0	150.00	0.00	0.00
311	2	155.00	45.00	0.00
312	0	155.00	40.00	0.00
313	0	155.00	35.00	0.00
314	0	155.00	30.00	0.00
315	0	155.00	25.00	0.00
316	0	155.00	20.00	0.00
317	0	155.00	15.00	0.00
318	0	155.00	10.00	0.00
319	0	155.00	5.00	0.00
320	0	155.00	0.00	0.00
321	2	160.00	45.00	0.00
322	0	160.00	40.00	0.00
323	0	160.00	35.00	0.00
324	0	160.00	30.00	0.00
325	0	160.00	25.00	0.00
326	0	160.00	20.00	0.00
327	0	160.00	15.00	0.00
328	0	160.00	10.00	0.00
329	0	160.00	5.00	0.00
330	0	160.00	0.00	0.00
331	2	165.00	45.00	0.00
332	0	165.00	40.00	0.00
333	0	165.00	35.00	0.00
334	0	165.00	30.00	0.00
335	0	165.00	25.00	0.00
336	0	165.00	20.00	0.00
337	0	165.00	15.00	0.00
338	0	165.00	10.00	0.00
339	0	165.00	5.00	0.00
340	0	165.00	0.00	0.00
341	2	170.00	45.00	0.00
342	0	170.00	40.00	0.00

343	0	170.00	35.00	0.00
344	0	170.00	30.00	0.00
345	0	170.00	25.00	0.00
346	0	170.00	20.00	0.00
347	0	170.00	15.00	0.00
348	0	170.00	10.00	0.00
349	0	170.00	5.00	0.00
350	0	170.00	0.00	0.00
351	2	175.00	45.00	0.00
352	0	175.00	40.00	0.00
353	0	175.00	35.00	0.00
354	0	175.00	30.00	0.00
355	0	175.00	25.00	0.00
356	0	175.00	20.00	0.00
357	0	175.00	15.00	0.00
358	0	175.00	10.00	0.00
359	0	175.00	5.00	0.00
360	0	175.00	0.00	0.00
361	2	180.00	45.00	0.00
362	0	180.00	40.00	0.00
363	0	180.00	35.00	0.00
364	0	180.00	30.00	0.00
365	0	180.00	25.00	0.00
366	0	180.00	20.00	0.00
367	0	180.00	15.00	0.00
368	0	180.00	10.00	0.00
369	0	180.00	5.00	0.00
370	0	180.00	0.00	0.00
371	2	185.00	45.00	0.00
372	0	185.00	40.00	0.00
373	0	185.00	35.00	0.00
374	0	185.00	30.00	0.00
375	0	185.00	25.00	0.00
376	0	185.00	20.00	0.00
377	0	185.00	15.00	0.00
378	0	185.00	10.00	0.00
379	0	185.00	5.00	0.00
380	0	185.00	0.00	0.00
381	2	190.00	45.00	0.00
382	0	190.00	40.00	0.00
383	0	190.00	35.00	0.00
384	0	190.00	30.00	0.00
385	0	190.00	25.00	0.00
386	0	190.00	20.00	0.00
387	0	190.00	15.00	0.00
388	0	190.00	10.00	0.00
389	0	190.00	5.00	0.00
390	0	190.00	0.00	0.00
391	2	195.00	45.00	0.00
392	0	195.00	40.00	0.00
393	0	195.00	35.00	0.00
394	0	195.00	30.00	0.00
395	0	195.00	25.00	0.00
396	0	195.00	20.00	0.00
397	0	195.00	15.00	0.00
398	0	195.00	10.00	0.00
399	0	195.00	5.00	0.00
400	0	195.00	0.00	0.00
401	2	200.00	45.00	0.00
402	0	200.00	40.00	0.00
403	0	200.00	35.00	0.00
404	0	200.00	30.00	0.00
405	0	200.00	25.00	0.00
406	0	200.00	20.00	0.00
407	0	200.00	15.00	0.00
408	0	200.00	10.00	0.00
409	0	200.00	5.00	0.00
410	0	200.00	0.00	0.00

Nodal Flows and Heads						
Node	Head	Percentage of available head	Flow			
1	0.5150E+02	100.0 %	0.2367E+00	16	0.4771E+02	41.7 %
2	0.4729E+02	35.2 %		17	0.4771E+02	41.7 %
3	0.4775E+02	42.4 %		18	0.4771E+02	41.7 %
4	0.4771E+02	41.6 %		19	0.4771E+02	41.7 %
5	0.4771E+02	41.7 %		20	0.4771E+02	41.7 %
6	0.4771E+02	41.7 %		21	0.5150E+02	100.0 %
7	0.4771E+02	41.7 %		22	0.4728E+02	35.1 %
8	0.4771E+02	41.7 %		23	0.4776E+02	42.4 %
9	0.4771E+02	41.7 %		24	0.4771E+02	41.6 %
10	0.4771E+02	41.7 %		25	0.4771E+02	41.7 %
11	0.5150E+02	100.0 %	0.4737E+00	26	0.4771E+02	41.7 %
12	0.4729E+02	35.2 %		27	0.4771E+02	41.7 %
13	0.4776E+02	42.4 %		28	0.4771E+02	41.7 %
14	0.4771E+02	41.6 %		29	0.4771E+02	41.7 %
15	0.4771E+02	41.7 %		30	0.4771E+02	41.7 %
33	0.4776E+02	42.5 %		31	0.5150E+02	100.0 %
34	0.4770E+02	41.6 %		32	0.4727E+02	34.9 %
35	0.4771E+02	41.7 %				
36	0.4771E+02	41.7 %		83	0.4780E+02	43.1 %
37	0.4771E+02	41.7 %		84	0.4769E+02	41.4 %
38	0.4771E+02	41.7 %	0.4781E+00	85	0.4771E+02	41.8 %
39	0.4771E+02	41.7 %		86	0.4771E+02	41.7 %
40	0.4771E+02	41.7 %		87	0.4771E+02	41.7 %
41	0.5150E+02	100.0 %		88	0.4771E+02	41.7 %
42	0.4726E+02	34.7 %		89	0.4771E+02	41.7 %
43	0.4777E+02	42.6 %		90	0.4771E+02	41.7 %
44	0.4770E+02	41.6 %		91	0.5150E+02	100.0 %
45	0.4771E+02	41.7 %		92	0.4713E+02	32.8 %
46	0.4771E+02	41.7 %		93	0.4782E+02	43.3 %
47	0.4771E+02	41.7 %		94	0.4769E+02	41.3 %
48	0.4771E+02	41.7 %	0.4808E+00	95	0.4772E+02	41.8 %
49	0.4771E+02	41.7 %		96	0.4771E+02	41.7 %
50	0.4771E+02	41.7 %		97	0.4771E+02	41.7 %
51	0.5150E+02	100.0 %		98	0.4771E+02	41.7 %
52	0.4724E+02	34.5 %		99	0.4771E+02	41.7 %
53	0.4777E+02	42.7 %		100	0.4771E+02	41.7 %
54	0.4770E+02	41.6 %		101	0.5150E+02	100.0 %
55	0.4771E+02	41.7 %		102	0.4709E+02	32.2 %
56	0.4771E+02	41.7 %		103	0.4783E+02	43.6 %
57	0.4771E+02	41.7 %		104	0.4768E+02	41.3 %
58	0.4771E+02	41.7 %	0.4841E+00	105	0.4772E+02	41.8 %
59	0.4771E+02	41.7 %		106	0.4771E+02	41.7 %
60	0.4771E+02	41.7 %		107	0.4771E+02	41.7 %
61	0.5150E+02	100.0 %		108	0.4771E+02	41.7 %
62	0.4722E+02	34.1 %		109	0.4771E+02	41.7 %
63	0.4778E+02	42.8 %		110	0.4771E+02	41.7 %
64	0.4770E+02	41.5 %		111	0.5083E+02	89.8 %
65	0.4771E+02	41.7 %		112	0.4723E+02	34.3 %
66	0.4771E+02	41.7 %		113	0.4780E+02	43.1 %
67	0.4771E+02	41.7 %		114	0.4769E+02	41.4 %
68	0.4771E+02	41.7 %	0.4881E+00	115	0.4771E+02	41.8 %
69	0.4771E+02	41.7 %		116	0.4771E+02	41.7 %
70	0.4771E+02	41.7 %		117	0.4771E+02	41.7 %
71	0.5150E+02	100.0 %		118	0.4771E+02	41.7 %
72	0.4719E+02	33.7 %		119	0.4771E+02	41.7 %
73	0.4779E+02	42.9 %		120	0.4771E+02	41.7 %
74	0.4770E+02	41.5 %		121	0.5018E+02	79.6 %
75	0.4771E+02	41.7 %		122	0.4736E+02	36.3 %
76	0.4771E+02	41.7 %		123	0.4777E+02	42.6 %
77	0.4771E+02	41.7 %		124	0.4770E+02	41.5 %
78	0.4771E+02	41.7 %	0.4926E+00	125	0.4771E+02	41.7 %
79	0.4771E+02	41.7 %		126	0.4771E+02	41.7 %
80	0.4771E+02	41.7 %		127	0.4771E+02	41.7 %
81	0.5150E+02	100.0 %		128	0.4771E+02	41.7 %
82	0.4716E+02	33.3 %		129	0.4771E+02	41.7 %
				130	0.4771E+02	41.7 %
				131	0.4953E+02	69.6 %
				132	0.4748E+02	38.2 %

133	0.4774E+02	42.2 %		203	0.4756E+02	39.4 %	
134	0.4770E+02	41.6 %		204	0.4775E+02	42.3 %	
135	0.4771E+02	41.7 %		205	0.4770E+02	41.6 %	
136	0.4771E+02	41.7 %		206	0.4771E+02	41.7 %	
137	0.4771E+02	41.7 %		207	0.4771E+02	41.7 %	
138	0.4771E+02	41.7 %		208	0.4771E+02	41.7 %	
139	0.4771E+02	41.7 %		209	0.4771E+02	41.7 %	
140	0.4771E+02	41.7 %		210	0.4771E+02	41.7 %	
141	0.4888E+02	59.7 %		211	0.4500E+02	0.0 %	-0.5191E+01
142	0.4761E+02	40.1 %		212	0.4831E+02	50.9 %	
143	0.4772E+02	41.8 %		213	0.4757E+02	39.6 %	
144	0.4771E+02	41.7 %		214	0.4774E+02	42.2 %	
145	0.4771E+02	41.7 %		215	0.4770E+02	41.6 %	
146	0.4771E+02	41.7 %		216	0.4771E+02	41.7 %	
147	0.4771E+02	41.7 %		217	0.4771E+02	41.7 %	
148	0.4771E+02	41.7 %		218	0.4771E+02	41.7 %	
149	0.4771E+02	41.7 %		219	0.4771E+02	41.7 %	
150	0.4771E+02	41.7 %		220	0.4771E+02	41.7 %	
151	0.4824E+02	49.8 %		221	0.4510E+02	1.5 %	0.0000E+00
152	0.4773E+02	42.0 %		222	0.4824E+02	49.9 %	
153	0.4769E+02	41.4 %		223	0.4760E+02	39.9 %	
154	0.4771E+02	41.8 %		224	0.4774E+02	42.1 %	
155	0.4771E+02	41.7 %		225	0.4770E+02	41.6 %	
156	0.4771E+02	41.7 %		226	0.4771E+02	41.7 %	
157	0.4771E+02	41.7 %		227	0.4771E+02	41.7 %	
158	0.4771E+02	41.7 %		228	0.4771E+02	41.7 %	
159	0.4771E+02	41.7 %		229	0.4771E+02	41.7 %	
160	0.4771E+02	41.7 %		230	0.4771E+02	41.7 %	
161	0.4759E+02	39.9 %		231	0.4519E+02	2.9 %	-0.1819E-11
162	0.4785E+02	43.8 %		232	0.4818E+02	49.0 %	
163	0.4767E+02	41.0 %		233	0.4761E+02	40.2 %	
164	0.4772E+02	41.9 %		234	0.4773E+02	42.0 %	
165	0.4771E+02	41.7 %		235	0.4771E+02	41.6 %	
166	0.4771E+02	41.7 %		236	0.4771E+02	41.7 %	
167	0.4771E+02	41.7 %		237	0.4771E+02	41.7 %	
168	0.4771E+02	41.7 %		238	0.4771E+02	41.7 %	
169	0.4771E+02	41.7 %		239	0.4771E+02	41.7 %	
170	0.4771E+02	41.7 %		240	0.4771E+02	41.7 %	
171	0.4695E+02	30.0 %		241	0.4527E+02	4.1 %	0.1592E-11
172	0.4797E+02	45.7 %		242	0.4813E+02	48.1 %	
173	0.4764E+02	40.7 %		243	0.4763E+02	40.5 %	
174	0.4773E+02	41.9 %		244	0.4773E+02	41.9 %	
175	0.4771E+02	41.6 %		245	0.4771E+02	41.6 %	
176	0.4771E+02	41.7 %		246	0.4771E+02	41.7 %	
177	0.4771E+02	41.7 %		247	0.4771E+02	41.7 %	
178	0.4771E+02	41.7 %		248	0.4771E+02	41.7 %	
179	0.4771E+02	41.7 %		249	0.4771E+02	41.7 %	
180	0.4771E+02	41.7 %		250	0.4771E+02	41.7 %	
181	0.4631E+02	20.1 %		251	0.4534E+02	5.3 %	-0.4547E-12
182	0.4809E+02	47.6 %		252	0.4808E+02	47.4 %	
183	0.4762E+02	40.2 %		253	0.4765E+02	40.7 %	
184	0.4773E+02	42.0 %		254	0.4772E+02	41.9 %	
185	0.4770E+02	41.6 %		255	0.4771E+02	41.7 %	
186	0.4771E+02	41.7 %		256	0.4771E+02	41.7 %	
187	0.4771E+02	41.7 %		257	0.4771E+02	41.7 %	
188	0.4771E+02	41.7 %		258	0.4771E+02	41.7 %	
189	0.4771E+02	41.7 %		259	0.4771E+02	41.7 %	
190	0.4771E+02	41.7 %		260	0.4771E+02	41.7 %	
191	0.4566E+02	10.1 %		261	0.4541E+02	6.4 %	0.6821E-12
192	0.4822E+02	49.5 %		262	0.4803E+02	46.7 %	
193	0.4759E+02	39.8 %		263	0.4766E+02	40.9 %	
194	0.4774E+02	42.1 %		264	0.4772E+02	41.8 %	
195	0.4770E+02	41.6 %		265	0.4771E+02	41.7 %	
196	0.4771E+02	41.7 %		266	0.4771E+02	41.7 %	
197	0.4771E+02	41.7 %		267	0.4771E+02	41.7 %	
198	0.4771E+02	41.7 %		268	0.4771E+02	41.7 %	
199	0.4771E+02	41.7 %		269	0.4771E+02	41.7 %	
200	0.4771E+02	41.7 %		270	0.4771E+02	41.7 %	
201	0.4500E+02	0.0 %	-0.3308E+02	271	0.4548E+02	7.3 %	-0.1137E-11
202	0.4835E+02	51.5 %		272	0.4799E+02	46.0 %	

273	0.4767E+02	41.1 %		343	0.4773E+02	41.9 %	
274	0.4772E+02	41.8 %		344	0.4770E+02	41.6 %	
275	0.4771E+02	41.7 %		345	0.4771E+02	41.7 %	
276	0.4771E+02	41.7 %		346	0.4771E+02	41.7 %	
277	0.4771E+02	41.7 %		347	0.4771E+02	41.7 %	
278	0.4771E+02	41.7 %		348	0.4771E+02	41.7 %	
279	0.4771E+02	41.7 %		349	0.4771E+02	41.7 %	
280	0.4771E+02	41.7 %		350	0.4771E+02	41.7 %	
281	0.4553E+02	8.2 %	-0.1137E-11	351	0.4580E+02	12.2 %	0.0000E+00
282	0.4795E+02	45.4 %		352	0.4778E+02	42.8 %	
283	0.4768E+02	41.3 %		353	0.4773E+02	42.0 %	
284	0.4771E+02	41.7 %		354	0.4770E+02	41.6 %	
285	0.4771E+02	41.7 %		355	0.4771E+02	41.7 %	
286	0.4771E+02	41.7 %		356	0.4771E+02	41.7 %	
287	0.4771E+02	41.7 %		357	0.4771E+02	41.7 %	
288	0.4771E+02	41.7 %		358	0.4771E+02	41.7 %	
289	0.4771E+02	41.7 %		359	0.4771E+02	41.7 %	
290	0.4771E+02	41.7 %		360	0.4771E+02	41.7 %	
291	0.4559E+02	9.0 %	0.4547E-12	361	0.4582E+02	12.5 %	0.4547E-12
292	0.4792E+02	44.9 %		362	0.4777E+02	42.7 %	
293	0.4769E+02	41.4 %		363	0.4773E+02	42.0 %	
294	0.4771E+02	41.7 %		364	0.4770E+02	41.6 %	
295	0.4771E+02	41.7 %		365	0.4771E+02	41.7 %	
296	0.4771E+02	41.7 %		366	0.4771E+02	41.7 %	
297	0.4771E+02	41.7 %		367	0.4771E+02	41.7 %	
298	0.4771E+02	41.7 %		368	0.4771E+02	41.7 %	
299	0.4771E+02	41.7 %		369	0.4771E+02	41.7 %	
300	0.4771E+02	41.7 %		370	0.4771E+02	41.7 %	
301	0.4563E+02	9.7 %	-0.2274E-12	371	0.4583E+02	12.8 %	-0.4547E-12
302	0.4789E+02	44.4 %		372	0.4776E+02	42.5 %	
303	0.4770E+02	41.6 %		373	0.4774E+02	42.1 %	
304	0.4771E+02	41.7 %		374	0.4770E+02	41.6 %	
305	0.4771E+02	41.7 %		375	0.4771E+02	41.7 %	
306	0.4771E+02	41.7 %		376	0.4771E+02	41.7 %	
307	0.4771E+02	41.7 %		377	0.4771E+02	41.7 %	
308	0.4771E+02	41.7 %		378	0.4771E+02	41.7 %	
309	0.4771E+02	41.7 %		379	0.4771E+02	41.7 %	
310	0.4771E+02	41.7 %		380	0.4771E+02	41.7 %	
311	0.4568E+02	10.4 %	-0.2274E-12	381	0.4584E+02	12.9 %	0.2274E-12
312	0.4786E+02	44.0 %		382	0.4776E+02	42.4 %	
313	0.4771E+02	41.7 %		383	0.4774E+02	42.1 %	
314	0.4771E+02	41.6 %		384	0.4770E+02	41.5 %	
315	0.4771E+02	41.7 %		385	0.4771E+02	41.7 %	
316	0.4771E+02	41.7 %		386	0.4771E+02	41.7 %	
317	0.4771E+02	41.7 %		387	0.4771E+02	41.7 %	
318	0.4771E+02	41.7 %		388	0.4771E+02	41.7 %	
319	0.4771E+02	41.7 %		389	0.4771E+02	41.7 %	
320	0.4771E+02	41.7 %		390	0.4771E+02	41.7 %	
321	0.4571E+02	11.0 %	-0.9095E-12	391	0.4585E+02	13.0 %	0.4547E-12
322	0.4784E+02	43.7 %		392	0.4775E+02	42.3 %	
323	0.4772E+02	41.8 %		393	0.4774E+02	42.1 %	
324	0.4771E+02	41.6 %		394	0.4770E+02	41.5 %	
325	0.4771E+02	41.7 %		395	0.4771E+02	41.7 %	
326	0.4771E+02	41.7 %		396	0.4771E+02	41.7 %	
327	0.4771E+02	41.7 %		397	0.4771E+02	41.7 %	
328	0.4771E+02	41.7 %		398	0.4771E+02	41.7 %	
329	0.4771E+02	41.7 %		399	0.4771E+02	41.7 %	
330	0.4771E+02	41.7 %		400	0.4771E+02	41.7 %	
331	0.4575E+02	11.5 %	0.9095E-12	401	0.4585E+02	13.1 %	-0.2274E-12
332	0.4782E+02	43.3 %		402	0.4775E+02	42.3 %	
333	0.4772E+02	41.9 %		403	0.4774E+02	42.1 %	
334	0.4770E+02	41.6 %		404	0.4770E+02	41.5 %	
335	0.4771E+02	41.7 %		405	0.4771E+02	41.7 %	
336	0.4771E+02	41.7 %		406	0.4771E+02	41.7 %	
337	0.4771E+02	41.7 %		407	0.4771E+02	41.7 %	
338	0.4771E+02	41.7 %		408	0.4771E+02	41.7 %	
339	0.4771E+02	41.7 %		409	0.4771E+02	41.7 %	
340	0.4771E+02	41.7 %		410	0.4771E+02	41.7 %	
341	0.4577E+02	11.9 %	-0.9095E-12				
342	0.4780E+02	43.1 %					

Flow = 3.8272E+01

## **VITA**

Senda Ozkan was born in Adana, Turkey, in 1970. She graduated from Middle East Technical University, Ankara, Turkey, in 1992 with a degree of Bachelor of Science in civil engineering. After graduating, she worked as a Project Engineer with TEMAT AS, Ankara, Turkey. She enrolled in Louisiana State University's graduate engineering program in the spring of 1995. She graduated in the fall of 1996 with a master's degree in civil engineering, and continued to her graduate studies at Louisiana State University. She is a registered Professional Engineer and currently works as an Environmental Staff Engineer with Gulf Engineers and Consultants, Inc., Baton Rouge, Louisiana. She is a candidate for a doctoral degree in civil engineering at Louisiana State University.



# Exhibit B

Engineering and Design  
DRILLING IN EARTH EMBANKMENT DAMS AND LEVEES

1. Purpose. This regulation establishes policy and requirements and provides guidance for drilling in dam and levee earth embankments and/or their earth and rock foundations. The primary purpose of this regulation is to prevent damage to embankments and their foundations from hydraulic fracturing, erosion, filter/drain contamination, heave, or other mechanisms during drilling operations, sampling, in-situ testing, grouting, instrumentation installation, borehole completion, and borehole abandonment.
2. Applicability. This regulation applies to all major subordinate commands (MSC), district commands, laboratories, and field operating activities having Civil Works and/or Military Program responsibilities. It applies to in-house and contracted drilling efforts for earth embankments or foundations associated with all dams and levees that have a federal interest.
3. Distribution. This regulation is approved for public release; distribution is unlimited.
4. References. References are listed in Appendix A.
5. Background. Drilling into, in close proximity to, or through embankment dams and levees and their foundations may pose significant risk to the structures. Water, compressed air, and various drilling fluids have been used as circulating media while drilling through earth embankments and their foundations. Although these methods have been successful in accomplishing the intended purposes, there have been incidents of damage to embankments and foundations. While using air (including air with foam), there have been reports of loss of circulation with pneumatic fracturing of the embankment as evidenced by connections to other borings and blowouts on embankment slopes. While using water and drilling mud as the circulating medium, there have been similar reports of erosion and/or hydraulic fracturing of the embankment or foundation materials. Conversely, there have been cases where heave, borehole collapse and significant disturbance have occurred while drilling in granular materials below the groundwater level. This typically has been the result of not using a proper drilling fluid to balance the water pressures in the soil or using high energy systems that induce heave in order to evacuate the cuttings. There is a delicate balance between too much induced fluid pressure that will cause hydraulic fracture and not enough fluid pressure that will result in borehole instability, heave, or significant sample disturbance. Other potential damaging effects include: creating preferential seepage paths due to improper backfilling, inadequate protection of embankment from drilling fluids during foundation rock coring, erosion and widening of cracks, and inadvertently clogging filters or drains with drilling fluid or grout. All drilling and associated activities that use fluid or other circulation or stabilization media need to be evaluated for the potential to hydraulically



fracture the embankment or foundation. These activities include but are not limited to the use of drilling fluids, backfilling borings after completion, backfill grouting of instrumentation, backfill grouting of casings, water testing for permeability, piezometer rehabilitation, etc. The risk will vary with the selected methods and the site conditions. Every drilling operation must be well thought out and must have benefits of successful completion that confidently outweigh the risk of potential negative impacts. The following paragraphs describe the general concerns associated with each type of potential damage.

a. Hydraulic Fracturing. Excessive pressures from water, air, drilling fluid, or grout can fracture embankment and foundation materials. Hydraulic fracturing problems have occurred while drilling in embankments as evidenced by reports of loss of fluid circulation, blowouts into nearby borings, seepage of drilling fluids on the face of the embankment, and other similar situations. Hydraulic fracture can occur in both cohesive materials and cohesionless materials, and bedrock. It has been found that in soils, hydraulic fracturing can occur when the borehole pressure exceeds the lowest total confining stress (minimum principal stress  $\sigma_3$ ) plus some additional strength. The additional strength can be approximated by the undrained strength of the soil. The minor principal confining stress ( $\sigma_3$ ) in a normally consolidated soil with a level ground condition is typically the horizontal stress, which can be reasonably estimated. However, the minor principal confining stress in and under an embankment is difficult to determine and can vary significantly from idealized geostatic conditions. Effects from the side slope geometry, piezometric surface, abutment configuration, foundation rock geometry, embedded structures, compaction stress, and settlement history all are significant and can influence in-situ stress conditions. Typical drilling methods that use circulation fluids can quickly create induced fluid pressures that exceed the minimum confining stress. This often occurs when the return path for the fluid clogs and the induced pressures quickly increase. The use of non-pressurized stabilizing fluids is preferable, yet in some subsurface conditions, hydraulic fracture can occur under gravity pressure. Low stress zones may exist within and under embankments. It is possible for the confining stress in these locations to be much less than the gravity pressure exerted by a drilling fluid or grout. Certain embankment locations and conditions have a higher potential for hydraulic fracturing due to geometric configurations that create zones of low confining stress. Sherard 1973 and 1986 are good references that provide a comprehensive evaluation of the issues along with numerous case histories. Locations and conditions where hydraulic fracturing by drilling media is more likely to occur and have the higher potential of damaging the structure include the following:

- (1) Near and over steep abutments that create low confining or tensile stress conditions.
- (2) Adjacent to rock overhangs on abutments.
- (3) Adjacent to buried structures or abrupt foundation geometry change that creates a differential settlement condition and a zone of lower soil stress transfer.
- (4) Adjacent to conduits where narrow zones of soil backfill were placed between the structure and rock face.
- (5) Dam cores that can experience more settlement than the adjacent shells.
- (6) Dams in very narrow valleys. Arching keeps full confining stresses from developing.
- (7) Near abutments where abrupt changes in geometry occur.

(8) In areas where the embankment is subject to differential settlement due to large differences in thickness of adjacent compressible foundation or embankment soils.

b. Erosion. The introduction of drilling fluids into cracks, either existing or formed by hydraulic fracture, can potentially cause erosion along the crack walls. This will enlarge the crack and could lead to an increased potential for internal erosion. Existing subsurface cracks are common in many dams and are often the result of differential settlement. The locations most at risk for existing cracks are typically the same areas that have low confining stress and have the highest risk for hydraulic fracture to occur.

c. Contamination of Filter/Drainage Features. In addition to hydraulic fracturing, the use of drilling fluids can pose a contamination risk for internal drainage features if the drill fluid or sealing grout migrates into and clogs the drain materials. Avoid drilling near drains or seepage blankets that may become contaminated by fluids. If drain penetration is justified, special provisions must be taken to prevent contamination. Special provisions may also be required for protecting the drainage features while backfilling the hole (such as placement of filter material through the zone of the drain or filter and installing lower and upper seals).

d. Heave and Sample Disturbance. Drilling programs that include performing in-situ tests or undisturbed sampling may require the use of drilling fluid to offset the confining stress relieved by the drilling of the hole. There have been cases where the failure to prevent stress relief or heave of granular soils below the water table have led to invalid in-situ test results and subsequently invalid interpretation of the subsurface conditions. This has occurred for both tests performed in drill holes and test performed in casings installed by methods that did not control heave or disturbance. Reclamation DSO 98-17 (1999) contains methods to deal with heaving sands while drilling and performing Standard Penetration Tests. If high quality undisturbed samples of fine grained soils are required for shear strength testing, then drilling mud may be required to prevent the soil from failing in undrained triaxial extension. See Ladd and DeGroot (2004) for a discussion on clay sample disturbance due to drilling.

6. Policy. This regulation provides guidance for investigation, maintenance, and remediation drilling in and near embankment dams and levees and/or their earth and rock foundations, including investigation planning, site preparation, borehole advancement, subsurface testing, instrumentation installation, piezometer and well rehabilitation, grouting, and borehole completion. It identifies drilling program plan requirements, restrictions on drilling fluids, drilling procedures to minimize risk of damage, borehole completion requirements, and prescribes personnel requirements, and the review and approval processes. It is the responsibility of the District Dam or Levee Safety Officer (DSO or LSO) to assure compliance with the restrictions and procedures outlined in this regulation.

a. Drilling Program Plan. An approved Drilling Program Plan (DPP) is required prior to any drilling, sampling, grouting, or any other invasive in-situ testing or exploration. This includes drilling activities related to investigation, maintenance, and remediation. When planning an investigation or remediation program, the data needs must be weighed against the potential risks of damage created by the drilling process. In general, all drilling and investigation should be targeted to obtain information related to a specific failure mode identified from a Potential Failure Mode Analysis (PFMA). For dams, the justification for drilling must include an approved

recommendation from a risk assessment performed in support of the Dam Safety risk management process described in ER 1110-2-1156 Safety of Dams - Policy and Procedures. If the structure has not had a PFMA, a thorough evaluation similar to the PFMA process must be performed and presented in the DPP to show that the drilling is justified. It is paramount that all existing subsurface information is thoroughly evaluated and understood by the exploration team prior to developing a plan for additional drilling. In order to understand and communicate subsurface conditions and estimate drilling risks, the existing subsurface information must be assimilated into essential plan and section drawings showing the proposed drill holes, target sample areas and/or proposed instrumentation. For critical or complicated drilling programs the Geotechnical and Geology Community of Practice leads can be contacted to obtain recommendations for subject matter experts to assist in developing the DPP. Specific requirements for the DPP are included in Appendix B.

b. Restrictions on the Use of Drilling Fluids. All drilling programs in dams and levees should be designed to minimize the need for any drilling fluid such as air, gas, water, mud, polymers, slurries or any other drilling fluid that could pressurize the borehole soils. If the drilling objective can be performed using dry methods such as augers or sonic drilling they should be employed in lieu of methods that require fluids. If drilling fluids must be used due to the drilling objective or the subsurface conditions, the DPP must contain an analysis of the potential to cause damage and a plan that covers the measures that will be used to minimize the risk. The use of pressurized air or foam should only be considered when drilling in materials that will not transmit pressures to the soil core or other critical features or when the air pressure is reliably isolated from the borehole soils. Drilling in an open graded rockfill shell may be an example of when using air may be appropriate. All DPPs that propose the use of stabilizing or circulating fluids or other media will require additional review and approval as described in paragraph 6f.

c. Drilling Procedures. As there are many existing and potentially new methods for drilling and sampling that may be implemented on dams and levees, this regulation will not provide specific procedures. Most procedures are documented in applicable standards and reference documents. There are however, some general procedures that should be followed when using drilling fluids to limit the risk of damage.

(1) Tools should be sized and designed to minimize the likelihood of the return flow clogging. Methods that require the cuttings to flow through a small annulus between the tools or casing and the borehole wall should not be used.

(2) If possible, fluid discharges from the bit should be upward. A downward discharge increases the chance of clogging which could lead to a pressure spike. A lateral discharge into the sidewalls could lead to excessive disturbance or erosion.

(3) Lower and raise drill tools slowly to avoid pressure changes in the drill hole; this is especially important when using tools with restricted annulus space below the groundwater table as the pressure changes are more severe and can lead to suction and surging problems.

(4) Drilling feed rate must be slow enough to avoid crowding the bit and, thus, minimize the chance of inducing fracturing. The bit must be of a design such that pressure buildup is minimized.

(5) Drilling media properties, pressure, and return should be continuously monitored. A floating needle pressure valve is required to record maximum pressure spikes that can occur instantaneously and are often unnoticed.

(6) In some conditions, casing can be advanced ahead of the drilling bit to reduce the risk of hydraulic fracturing by confining the drilling fluids within the casing.

(7) When core drilling rock, the embankment or foundation soil above top of rock must be protected and isolated from the circulating drilling fluid. Fractures in the bedrock must be considered as potential flow paths in contact with the overlying soil.

(8) In situations where the presence of significant artesian pressure is suspected, which are common at the toe of dams, it may be necessary to use weighted drilling muds or raise the drill rig or install surface casing for pressure control along with the use of drilling mud. In some cases there may be a high risk of initiating internal erosion by drilling borings or excavating test pits in these areas. Emergency materials to stop progressive erosion in an excavation, a trench, or a borehole must be on site and readily available. For this situation, it is recommended to stockpile fine (C33 concrete sand) and coarse processed aggregates to filter and plug the excavation. Specific details such as height of the drill pad and amount of surface casing must be developed on a case-by-case basis dependent upon specific site conditions.

d. Borehole Completion. All boreholes and other penetrations (including direct push sampling, Cone Penetration Test soundings, Standard Penetration Testing, Becker Penetration Testing,) in and around embankment dams and levees must be sealed after completion. Completing a borehole by backfilling with drill cuttings is not acceptable. All boreholes and similar penetrations in the impervious portions of an embankment dam or levee and their foundations must be backfilled by tremie placed cement-bentonite grout or bentonite pellets/chips. The DPP must address the possibility of confined and separate ground water aquifers and demonstrate safe completion which avoids cross-contamination and leakage. The grout must be designed to obtain strength equal to or greater than the soil. Note that some instrumentation installations may require additional considerations for the grout strength. Gravity grouting techniques should be used for backfilling boreholes. For borings that penetrate zones with low confining stress it is possible to induce hydraulic fracturing from the gravity pressure. When grouting borings in these locations or if significant grout losses are observed, the grout backfilling should be done in stages allowing the grout to set between stages. For pervious portions of the dam or levee, the borehole must be backfilled by tremie placement of granular materials that are sized to provide drainage without being susceptible to migration through the pervious embankment or foundation materials or segregation during placement. Lutenecker, et.al. (1995) is a good source for borehole backfill guidelines. Special procedures and materials may be required for installation of instrumentation in boreholes.

e. Drilling Personnel. Drill rig operators must have a minimum of 5 years experience drilling with the equipment and procedures described in the drilling program. The drill rig operator must also be familiar with these guidelines. All drilling activities on USACE dams or levees must be conducted in the presence of a geotechnical engineer that is a licensed professional engineer or a licensed professional geologist who will be responsible for maintaining the integrity of the structure.

31 Dec 14

f. Approval Requirements. Drilling Program Plans must be reviewed and approved by the District Dam Safety Officer (Dams) or Levee Safety Officer (Levees). If any drilling fluid or other stabilizing or circulating media is proposed, a technical review performed by the Geotechnical and Materials Community of Practice (G&M CoP) Standing Committee on Drilling and Instrumentation is required. The plan will then require approval from the District DSO/LSO pending satisfactory resolution of the technical review comments. The Standing Committee on Drilling and Instrumentation will be chaired by the G&M CoP Lead, co-chaired and managed by the Risk Management Center, and staffed with G&M CoP experts.

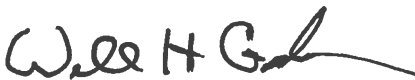
g. Reporting. All incidents of damage or potential damage related to drilling and associated activities for dams must be reported following procedures outlined in Chapter 13 Reporting Evidence of Distress in Civil Works Structures of ER 1110-2-1156 Safety of Dams- Policy and Procedures. Damage in levees must be reported to the Levee Safety Officers and Levee Safety Program Managers in the District, MSC, and Headquarters.

h. Exemptions. Drilling required for immediate emergency measures where delays required to develop the DPP and obtain approvals would result in unacceptable risk of damage or failure, may be exempted from the requirements to prepare a DPP by the District DSO/LSO. Emergency drilling should be appropriately expedited but should follow the general guidelines presented in this regulation. No other exemptions or deviations from these requirements may be made.

7. Environmental Operating Principles. The user of this ER, as a member of a Project Delivery Team, is responsible for seeking opportunities to incorporate the Environmental Operating Principles (EOPs) wherever possible. A listing of the EOPs is available at:  
<http://www.usace.army.mil/Missions/Environmental/EnvironmentalOperatingPrinciples.aspx>.

FOR THE COMMANDER:

2 Appendices  
Appendix A - References and Resources  
Appendix B - Drilling Program Plan

  
WILLIAM H. GRAHAM  
COL, EN  
Chief of Staff

## APPENDIX A

### References and Resources

#### Drilling Procedures

EM 1110-1-1804 Geotechnical Investigations (including Appendix F EM 1110-1-1906 Soil Sampling).

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ER 1110-2-1156 Safety of Dams- Policy and Procedures.

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## APPENDIX B

### Drilling Program Plan

An approved drilling program plan (DPP) is required for any exploration or remedial drilling (including grouting) work to occur in or near an embankment dam or levee or their foundations. When drilling is justified, an exploration team must be formed to determine and document the drilling program components required to adequately and safely address the project needs. The exploration team must thoroughly discuss the drilling program to ensure that the program minimizes risk and meets the project goals. The drilling program must be prepared by experienced geotechnical engineers and/or engineering geologists familiar with subsurface exploration techniques and methods, with advice from drilling specialists. The Lead engineer on the exploration team must be a registered professional engineer. This section describes the basic information that must be developed and included in the drilling program.

a. Objective and Justification. The objective of the drilling program must be clearly summarized including the purpose of the drilling and how the borings, samples, testing, instrumentation, etc. will be used. The need for the drilling must be thoroughly justified. Drilling should be minimized by first utilizing non-destructive methods including parametric analysis, the use of published correlations, and non-destructive geophysical testing. The justification must include documentation that shows the purpose is based obtaining information related to potential failure modes identified in an approved risk assessment in support of the dam or levee safety program. If an approved PFMA or risk assessment has not been performed, the exploration team must perform a thorough evaluation similar to the PFMA process and present a valid justification demonstrating that the drilling is required to obtain information related to a credible potential failure mode.

b. Exploration Team. List members of the exploration team used in developing the DPP. Include name, organization, title, registration, and years of experience.

c. Existing Information Review. In order to understand subsurface conditions, justify additional drilling, and estimate drilling risks, all relevant existing information must be assimilated and reviewed by the exploration team and then concisely summarized in the DPP. Information review typically includes, but is not limited to:

- (1) Geologic mapping, boring logs, driller's notes, and reports portraying information from previous investigations and construction.
- (2) Geotechnical files and reports including Site Characterization Reports.
- (3) Foundation Completion Reports.
- (4) Embankment Construction Reports.
- (5) Periodic Inspection or Periodic Assessment Reports.
- (6) As-built drawings.
- (7) Archived records.

(8) Other construction reports.

(9) Construction photos for both original embankment construction and any subsequent construction.

(10) Instrumentation plans, data, and reports.

(11) Project records available in district and project offices.

d. Essential Geologic and Engineering Drawings. The DPP must include a set of drawings depicting the current understanding of subsurface conditions, as they relate to the proposed work. This detailed set of foundation and embankment drawings typically requires a plan showing all previous and proposed subsurface investigation locations, profile drawings, and sections of the embankment in the areas proposed for exploration. The sections must be drawn to scale with no vertical exaggeration and must show the proposed borings along with all available factual information and appropriate geologic or engineering interpretations. The drawings should be updated regularly during the drilling operations to show conditions encountered and adjust geologic interpretations to help guide the program. The information on the plan, profile and sections must be detailed and include a summary of all data significant to the analytical and exploration needs such as:

(1) Embankment zones, including added berms, blankets, filters, and drains.

(2) Details of subsurface material classification.

(3) Geologic contacts and continuity interpretations supported by all nearby drilling and sampling details.

(4) Depth of the top of rock and all other zones of importance.

(5) Piezometer locations showing screened influence zones and recorded piezometric levels tied to the reservoir water level.

(6) Other instrumentation such as inclinometers, movement monuments, etc., shown in the context of the foundation geology contacts and interpretations.

(7) SPT blow counts or other test results defining engineering properties.

(8) Geophysical data, where useful (e.g. cross hole shear wave velocity profiles).

(9) Estimated extent of any zones of interest, including natural and made-made (grout holes).

(10) Seepage areas tied to geologic units, where possible.

(11) Location of all structures, including seepage control features, outlet works, etc.

(12) Location and types of any distress features (seepage, wet spots, sand boils, sinkholes, etc.).

Maintaining updated geologic sections and a plan during the drilling operations is important for making exploration changes and for responding to unusual or unexpected conditions or events. The process for accomplishing this must be outlined in the drilling program.

e. Drilling Scope and Methodology. The drilling program must include a summary of the scope and methods that will be used, including the following:

- (1) Number and location of proposed borings.
- (2) Utilities, surface and underground obstacles, and accessibility.
- (3) Materials expected to be drilled, sampled, and tested.
- (4) Depth, diameter, bearing, and inclination of borings.
- (5) Required sample type (disturbed or undisturbed), size, location, and reason for sampling.
- (6) Proposed laboratory testing.
- (7) Drilling, sampling, and testing methods.
- (8) Details of the proposed tools and drilling equipment.
- (9) Instrumentation and borehole completion requirements (influence zone, seals, etc.). Drill rig operators: Name and years of experience.
- (10) Field Supervision Personnel: Name, organization, title, registrations, years of experience.
- (11) Personnel responsible for logging materials and assuring geologic drawings are updated regularly during the drilling program.

f. Risk Evaluation. Include an evaluation of the risk of hydraulic fracturing, erosion, contamination of drainage features, heave, or any other damage. This should include:

- (1) A detailed description of any drilling fluid used including details on the circulation system, locations where fluid will contact soil, and circulation pressures that will be used.
- (2) Monitoring needs during drilling, and a contingency plan if loss of drilling fluid or other complications are observed during drilling.
- (3) Measures to minimize the risk of damage to the dam or foundation.
- (4) Measures to prevent the possibility of cross-contamination and leakage from confined and separate ground water aquifers.
- (5) Measures to prevent drill contact with structural features, such as conduits.
- (6) Nearby instruments whose behavior will be monitored during the investigation and the expected response including threshold and limit values, and contingency plans for unexpected response.
- (7) An emergency action plan including a list of emergency equipment and supplies to have onsite (phone/radio, filter materials, grout materials, etc.).



g. DSO/LSO Certification. Provide a certification page with the signature of the appropriate DSO/LSO. The certification must state: This Drilling Program Plan has been developed and reviewed by experienced professionals and is in compliance with all the requirements of ER 1110-1-1807. The proposed actions are justified and have been developed to minimize the likelihood of damage to the existing structure.

# Exhibit C





Water Resources ♦ Flood Control ♦ Water Rights

GILBERT COSIO, JR., P.E.  
MARC VAN CAMP, P.E.  
WALTER BOUREZ, III, P.E.  
RIC REINHARDT, P.E.  
DON TRIEU, P.E.  
DARREN CORDOVA, P.E.  
NATHAN HERSHEY, P.E., P.L.S.  
LEE G. BERGFELD, P.E.  
BEN TUSTISON, P.E.  
THOMAS ENGLER, P.E., CFM  
MICHAEL MONCRIEF, P.E.

ANGUS NORMAN MURRAY  
1913-1985

CONSULTANTS:  
JOSEPH I. BURNS, P.E.  
DONALD E. KIENLEN, P.E.

## MEMORANDUM

**DATE:** January 13, 2020  
**TO:** Melinda Terry, California Central Valley Flood Control Association  
**PREPARED BY:** Gilbert Cosio, Jr., MBK Engineers  
**SUBJECT:** Soil Investigations for Data Collection in the Delta IS/MND

---

We have reviewed the California Department of Water Resources (DWR) Initial Statement/Mitigated Negative Declaration (IS/MND) relative to "Soil Investigations for Data Collection in the Delta". Based on my 36 years of experience (curriculum vitae attached) with the levees, drainage, and irrigation in the Delta, we have a number of concerns that must be reviewed as part of the IS/MND as described, below.

Geotechnical exploration in the Delta involves penetrating through varying layers of soil into a pressurized aquifer. Therefore, any drilling should prepare for artesian flow and address long-term concerns that improper sealing of borings could lead to future seepage. These impacts can result in levee instability and levee failure, and long-term seepage issues that impact farming and increase drainage costs. In addition, compaction of fields caused by drilling equipment causes long-term farming impacts.

Therefore, the IS/MND should provide specific details on how it will address the following:

- Abandonment and sealing of the holes to prevent future seepage
- Preparation for, and measures to deal with, artesian flow that may occur during development of the borings
- Obtaining approval from levee maintaining agencies and the California Central Valley Flood Protection Board
- Evaluating farm fields that would be impacted by geotechnical drill rigs

If you have any questions, or require additional information, please call me at 916-456-4400.



---

Gilbert Cosio, Jr.

GC/nl  
8888.4 MELINDA TERRY 2020-01-13

Enclosure

**EDUCATION**

- ◆ University of California, Davis  
Completed course work for MS in Civil Engineering with emphasis in Water Resources, 1984
- ◆ University of Santa Clara  
BS in Civil Engineering, 1980

**PROFESSIONAL LICENSES AND SOCIETIES**

- ◆ Registered Civil Engineer in California
- ◆ Member, American Society of Civil Engineers
- ◆ Member, Tau Beta Pi, Engineering Honor Society
- ◆ Member, U.S. Committee on Irrigation and Drainage

**EXPERIENCE**

**1984 to Present**      **MBK Engineers, Sacramento, CA**

***Principal***

Civil engineer in fields of flood control, hydrology, hydraulics, water resources planning, drainage, water supply, surveying, and levee maintenance.

**1980 to 1983**      **Bechtel Corporation, San Francisco, CA**

***Civil/Structural Engineer***

Design and construction of concrete and steel involving structural analysis, seismic design, interdisciplinary coordination, field construction correspondence and temporary field assignments.

**EXPERIENCE HIGHLIGHTS****RECLAMATION DISTRICT LEVEE ENGINEERING**

Acts as public representative and provides consulting engineering service to 34 Sacramento/ San Joaquin Delta, Suisun Marsh and Sacramento River reclamation districts in regard to levee maintenance and rehabilitation. This includes levee rehabilitation design and construction, levee surveys, bank protection design and construction, resolution of seepage and subsidence problems, development of encroachment control criteria, maintenance inspections, maintenance recommendations, assistance with regulatory filing, environmental assessment assistance, assistance and participation in funding programs through the State and Federal governments, flood fight planning, coordination and hazard mitigation planning (1984 to Present).

Significant projects include a \$10 million full island levee rehabilitation project on Empire Tract (2016), and a \$1.5 million seepage berm on Grand Island (2013); development of Emergency Operations Plans and Flood Contingency Maps for nine San Joaquin County Reclamation Districts (2015), development of five-year levee rehabilitation plans for 22 reclamation districts (2010), importation of 625,000 cy of material from Decker Island to stabilize 10 miles of levee on four reclamation districts (2000 to 2004), design and construction of a habitat-friendly levee on Reclamation District No. 2110 (2001, 2005, and 2018), development of procedures to perform non-destructive subsurface surveys of the levees using electromagnetic technology (2005), design and construction of breach closures on Prospect Island (1996), McCormack-Williamson Tract (1997), and Little Mandeville Island (2001). Provided services to U.S. Army Corps of Engineers in regard to \$196 million CALFED Levee Stability Program (2008 to 2009). Provided flood fight participation and coordination, and disaster restoration through federal and state disaster assistance programs for floods of 1982, 1983, 1986, 1995, 1997, 1998, 2006, and 2017.

**HABITAT IMPROVEMENT IN CONJUNCTION WITH LEVEE REHABILITATION**

In role of engineering consultant to reclamation districts, extremely active in development of projects that benefit levees and provide habitat enhancement. Responsibilities include development of design plans, environmental



documentation, regulatory assistance, construction, and monitoring. Recent projects include design of a self-mitigating erosion repair site under the DWR FSRP program (2019), the development of habitat friendly levee design for preparation of return to tidal wetland (2016), development of plans to return Dutch Slough (RD 2137) to tidal habitat (2016), the Beaver Slough Habitat Improvement Project, which stabilized eroded sections of levee while providing marsh and shaded riverine aquatic habitat; the Decker Island Habitat Project that stabilized 10 miles of levee on four levee districts while creating 30 acres of tidal marsh habitat (2000 to 2004); the Lower Sacramento River Revegetation Demonstration Project, which consisted of construction and maintenance of vegetation through existing rip rap on Grand Island (2000); the Delta Channel Islands Demonstration Project, which evaluated the viability of using biotechnical bank protection in the Delta (1999 to 2005); design and construction of a habitat-friendly levee on McCormack-Williamson Tract (2001, 2005, and 2018); and bank protection demonstration projects on Holland Tract and McCormack-Williamson Tract, utilizing various methods to demonstrate the ability to incorporate vegetation in bank protection.

### **DRAINAGE FACILITIES ENGINEERING**

As consulting engineer to reclamation districts, responsibilities also include evaluation of drainage facilities. In 1992, performed research and reporting to the Regional Water Quality Control Board of all irrigation and drainage channels for all reclamation districts as required under the Inland Surface Waters Plan. Has performed numerous evaluations of drainage facilities including pump testing and evaluation, hydraulic and hydrologic evaluation of canals, and pump plant design and construction. Major projects include construction of new pumping plants on Reclamation District Nos. 551, 999, 2029, 2033, and 2065. Performed hydrology and hydraulics analysis of drainage systems of RD 551 and RD 3.

### **BOARDS AND COMMITTEES**

- ◆ Habitat Advisory Committee to the State of California Delta Levee Subventions Program
- ◆ Delta Channel Islands Work Group
- ◆ CALFED Levees & Channels Technical Team
- ◆ CALFED Levees & Channels Seismic Sub-Team
- ◆ CALFED Suisun Marsh Levees Sub-Team
- ◆ Delta Risk Management Strategy Technical Advisory Committee
- ◆ Delta Risk Management Strategy Steering Committee
- ◆ Lower Yolo Bypass Planning Forum
- ◆ Delta Vision Stakeholder Coordination Group
- ◆ Delta Conservancy Delta Dialogues Stakeholders Group
- ◆ Delta Stewardship Council Delta Climate Change Vulnerability Assessment and Strategy TAC
- ◆ Delta Conservancy Delta Salmon Rearing Habitat Study Advisory Group



# Exhibit D





R.D. No. 3 - Grand Island - Site Review of Boil Near Sacramento River Levee  
January 4, 1997

Looking at boil 400 ft. from levee toe downstream of Ryde at levee mile 8.15 on the  
Sacramento River levee; 1120 hours.  
(G. Cosio - Photographer)

PHOTO SOURCE:  
MBK ENGINEERS

RESPONDENTS EXHIBIT 6A





Boil on Grand Island south of Ryde.



CCC crews working around boil.

R.D. No. 3 - Boil on Right Bank of Sacramento River - 1/4/97

PHOTO SOURCE:  
MBK ENGINEERS

(M. Fortner - Photographer)

RESPONDENTS EXHIBIT 6B



CCC crew about 1/3 of the way into boil sandbag ring.



CCC crew constructing sandbag ring around boil.

R.D. No. 3 - Boil on Right Bank of Sacramento River - 1/4/97

PHOTO SOURCE:  
MBK ENGINEERS

(M. Fortner - Photographer)

RESPONDENTS EXHIBIT 6C





PHOTO SOURCE: KAREN CUNNINGHAM  
BRADFORD ISLAND LANDOWNER

RESPONDENTS EXHIBIT 7A





PHOTO SOURCE: KAREN CUNNINGHAM  
BRADFORD ISLAND LANDOWNER

**RESPONDENTS EXHIBIT 7B**



# Exhibit E



United States Department of Agriculture  
Natural Resources Conservation Service

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## **Part 631 Geology**

# **National Engineering Handbook**

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## **Chapter 11**

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# **Cone Penetrometer**

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Issued January 2012

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# Preface

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This new chapter replaces Soil Mechanics Note 11 (SMN-11), which was originally issued in 1984.

Materials in this chapter were adapted from the following publications:

- ASTM D5778, Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils
- Cone Penetration Testing in Geotechnical Practice, 1997, Lunne, T., P.K. Robertson, and J.J.M Powell.
- Cone Penetration Testing State-of-Practice, Mayne, P.W., 2007, National Cooperative Highway Research Program (NCHRP) Project 20-05, Topic 37-14, Washington DC. [http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp\\_syn\\_368.pdf](http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_syn_368.pdf).
- Guide to Cone Penetration Testing for Geotechnical Engineering, 3rd Edition, 2010, Robertson P.K., and K.L. Cabal.





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# Chapter 11

# Cone Penetrometer

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### 631.1100 Purpose and scope

The cone penetrometer test (CPT) provides valuable information in geotechnical investigations when used in conjunction with other equipment and procedures. This chapter describes the CPT and explains the equipment, field procedures, and application. It also describes some procedures and guidance for interpreting and using the test results. The working end of a typical cone penetrometer is shown in figure 11–1.

This manual is not intended to provide full details of geotechnical analyses. The primary references generally accepted by industry are listed and shown in the references at the end of this chapter.

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**Figure 11–1** Working end of cone penetrometer (*Photo courtesy of Gregg Drilling & Testing, Inc.*)



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### 631.1101 Introduction

Cone penetrometer testing (CPT) is a fast, effective, and relatively inexpensive system for collecting important soils parameters during a geotechnical site investigation. When used in conjunction with conventional drilling and sampling methods, it provides a more complete description of the subsurface conditions, thereby reducing uncertainty in design and construction.

CPT methods can be divided into two basic groups:

- geophysical logging and stratigraphic profiling
- specific test methods

Testing equipment consists of a cone on the end of a series of rods that are pushed hydraulically into the ground. The typical rate of penetration is 2 centimeters per second (~1 in/s), or 91 meters per hour (~300 ft/h). CPTs can be performed to depths exceeding 100 meters (~300 ft) with large-capacity pushing equipment.

CPT logging is fast and economical, particularly in soft soils. CPTs can also provide preliminary evaluations of soil parameters and provide quantitative estimates of various geotechnical parameters based on empirical correlations.

Specific tests measure soil properties at a particular point, while some in situ CPTs can characterize specific engineering properties, including shear strength and modulus of elasticity. They require the use of specialized equipment, however, and can be slower and more expensive. Because of the increased cost, they are best used in critical areas that have been previously identified.

CPTs can be used to screen subsurface conditions during preliminary geologic investigations and locate borings for subsequent detailed geologic investigations (refer to NEM531 and NEH631.02). Soundings can be used to pinpoint changes in the lithology (stratigraphy) and identify areas to be sampled. CPT is particularly useful in nonuniform foundations and where undisturbed samples are difficult to obtain.

CPT with modern equipment provides continuous readings of:

- point load or tip resistance ( $q_c$ )
- friction ( $f_s$ )
- porewater pressure ( $u$ )

Tip resistance is theoretically related to the undrained shear strength of a saturated, cohesive material and measured with an embedded load cell. The sleeve friction is theoretically related to the friction of the horizon being penetrated and measured using tension load cells embedded in the sleeve.

After the initial information is collected, the digital data are post-processed to provide numerical values for engineering analysis. The use of computer processing during field investigations has enabled immediate interpretation of CPT results.

Results of CPT can be used to make reliable estimates of settlement and undrained shear strength in areas where some basic information about the engineering properties of the soil is available. Results, however, should always be confirmed or correlated with laboratory analyses of actual samples.

The cone itself does not produce a sample. Test results are nonunique and must be verified and calibrated to the specific site. Fewer physical samples are required if the geology of the area and some of the engineering properties of the soil are understood. While the CPT equipment cannot obtain a sample, some samplers can also be pushed into the ground using CPT equipment.

Undisturbed soil sampling is vital to the success of a geotechnical investigation and should be considered a companion of CPT. CPT data complement undisturbed sampling and provide a significant volume of in situ information that is difficult to achieve in the lab. Comparing lab results of both shear and consolidation tests with CPT data reduces the uncertainty of either set of data.

Most of the commercially operated CPT rigs use electronic friction cone and piezocone penetrometers as standard practice. Soundings are presented digitally. In the United States, most CPT is performed using electrical cones. The mechanical CPT is, however, manufactured and used in some parts of the world, particularly in developing countries, because of the equipment's low cost, simplicity, and sturdiness.

## 631.1102 Applications

CPT results have two fundamental uses requiring specific sensors and equipment:

- Direct measurements are used to estimate geotechnical parameters, which can then be used in an analysis.
- CPT results can also be directly applied into geotechnical engineering designs.

Although older CPT versions had previously only delivered readings for  $q_c$ ,  $f_s$ , and  $u$ , recent improvements in the technology have greatly increased the CPT's utility in geotechnical investigations. Separate modules are now available with a wide range of sensors. The additional soundings generated are recorded simultaneously at the surface with the standard data in digital output. The new mechanical configurations are variable as well, with most added just behind the cone, some being retractable, and others with the capability to simultaneously measure porewater pressures. Separate modules that can be added to the cone include:

- temperature sensors, used to identify saturated zones
- video and still cameras
- microphones
- pH sensors, mounted either in the cone or on the surface of the probe
- pressure meters, which measure in situ (undrained) lateral stresses
- radioisotope detectors (gamma), used for determining density and water content

Modules used primarily for geoenvironmental investigations include:

- Oxygen exchange capacity, the electrical potential associated with the oxidation or reduction of a substance; or a measure of the tendency of a chemical species to acquire electrons in the reduction process.
- Laser/ultraviolet-induced fluorescence (LIF) measures hydrocarbons with polyaromatic constituents, such as benzene.

- Membrane interface probe (MIP) is used to locate volatiles in the subsurface. It has semi-quantitative capabilities and acts as an interface between contaminants in the subsurface, which diffuse across the membrane into an upward-moving gas stream, and the detector at the surface.
- Dielectric permittivity, which is based on the propagation of electromagnetic waves; indicate presence of organic contaminants in porewater with much more sensitivity than resistivity.

The common types of CPTs that are available for site characterization are listed in table 11–1.

The primary application of the CPT is for soil profiling and determining soil type using soil behavior type (SBT) graphs (fig. 11–2) that have been developed for this application. The numerical values are plotted on SBT graphs, from which the zone is identified. For example, cone resistance ( $q_c$ ) is high in sands, and the friction ratio ( $R_f$ ) is low, shown in zone 9 in figure 11–2. In soft clays,  $q_c$  is low and  $R_f$  is high, shown in zone 3.

CPT measures *state parameters* of the soil, which is one of a set of variables that describe the “state” of a dynamic system. They include void ratio ( $e_v$ ), unit weight

( $\gamma$ ), porosity ( $n$ ), and relative density ( $D_r$ ). These data are used to estimate the following geotechnical parameters of the materials, which then can be used in various geotechnical analyses:

- undrained shear strength ( $S_u$ )
- soil sensitivity ( $S_t$ )  $\frac{S_u}{\sigma'_{vo}}$
- undrained shear strength ratio,  $\sigma'_{vo}$
- stress history, overconsolidation ratio (OCR)

These data can also be applied directly to an engineering analysis, particularly in the analysis of load-settlement relationships and bearing capacity. CPT data can be used to develop factors for the bearing capacity analysis, including shape factors, load inclination factors, and the effects of groundwater and effective stress.

Table 11–2 shows reliability ratings of CPT data for design applications. The data presented are a synthesis on the state of practice in CPT undertaken during the National Cooperative Highway Research Program (Mayne 2007). A survey questionnaire was prepared for this program, directed at geotechnical engineers working for Departments of Transportation in 52 States and 12 provincial DOTs in Canada. Conclusions from this survey are summarized in table 11–3.

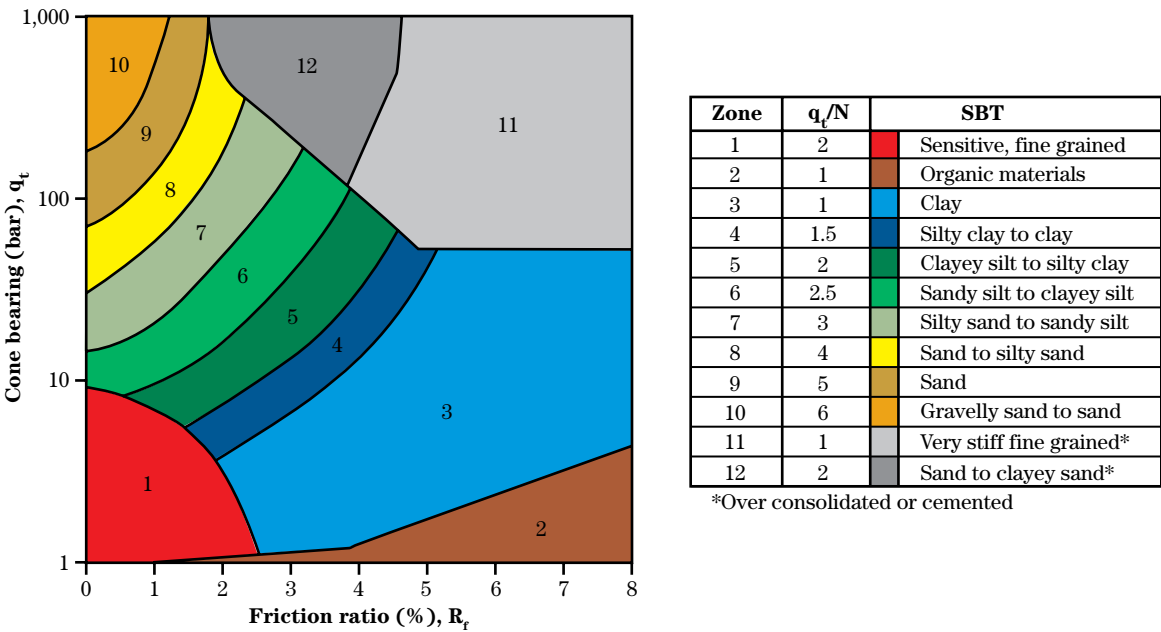
**Table 11–1** Basic CPTs used in site characterization (Mayne 2007)

Type of CPT	Acronym	Measurements taken	Applications
Mechanical cone penetration test	MCPT	$q_c$ and $f_s$ at 20-cm intervals. Uses inner and outer rods to convey loads uphole	Stratigraphic profiling, fill control, natural sands, hard ground
Electrical friction cone	ECPT	$q_c$ and $f_s$ (taken at 1- to 5-cm intervals)	Fill placement, natural sands, and soils above the groundwater interface
Piezocone penetration test	CPTu and PCPT	$q_c$ , $f_s$ , and either face $u_1$ or shoulder $u_2$ (taken at 1- to 5-cm intervals)	All soil types. Note: Requires $u_2$ for correction of $q_c$ to $q$ .
Piezocone with dissipation	CPTu	Same as CPTu with timed readings of $u_1$ or $u_2$ during decay, measured by stopping the penetration and measuring the decay of pore pressures with time	Normally conducted to 50% dissipation in silts and clays. Used to estimate compressibility and permeability
Seismic piezocone test with embedded geophones	SCPTu	Same as CPTu with downhole shear waves ( $V_s$ ) at 1-m intervals	Provides fundamental soil stiffness with depth: $G_{max} = \rho_t V_s^2$
Resistivity piezocone test	RCPTu	Same as CPTu with electrical conductivity or resistivity readings	Detect freshwater–saltwater interface, indicates contaminant plumes.

**Notes:**  $q_c$  = measured point stress or cone tip resistance  
 $f_s$  = measured sleeve friction  
 $u$  = penetration porewater pressure ( $u_1$  at face;  $u_2$  at shoulder)  
 $q_t$  = total cone resistance,  $V_s$  = shear wave velocity



**Figure 11–2** Soil behavior types (Robertson 1989)



**Table 11–2** Perceived applicability of the CPT/CPTu for various design problems (Mayne 2007)

Soil type	Pile design	Bearing capacity	Settlement*	Compaction control	Liquefaction
	CPT reliability rating				
Sand	1–2	1–2	2–3	1–2	1–2
Clay	1–2	1–2	2–3	3–4	1–2
Intermediate soils	1–2	2–3	2–3	2–3	1–2

Reliability rating: 1 = High; 2 = High to moderate; 3 = Moderate; 4 = Moderate to low; 5 = Low

**Table 11–3** Advantages and disadvantages of CPT

Advantages	Provides fast and continuous profiling
	Equipment is economical and productive
	Generates repeatable and reliable data that are not dependent on the operator
	Can identify thin horizons of low strength
	Reduces contact between field personnel and contaminated soil
	Strong theoretical basis for interpretation
Disadvantages	High initial capital investment
	Skilled operators are required
	No drill cuttings or soil samples are produced
	Limited penetration in gravels or cemented materials
	Data are unreliable in unsaturated conditions, particularly in clayey soils

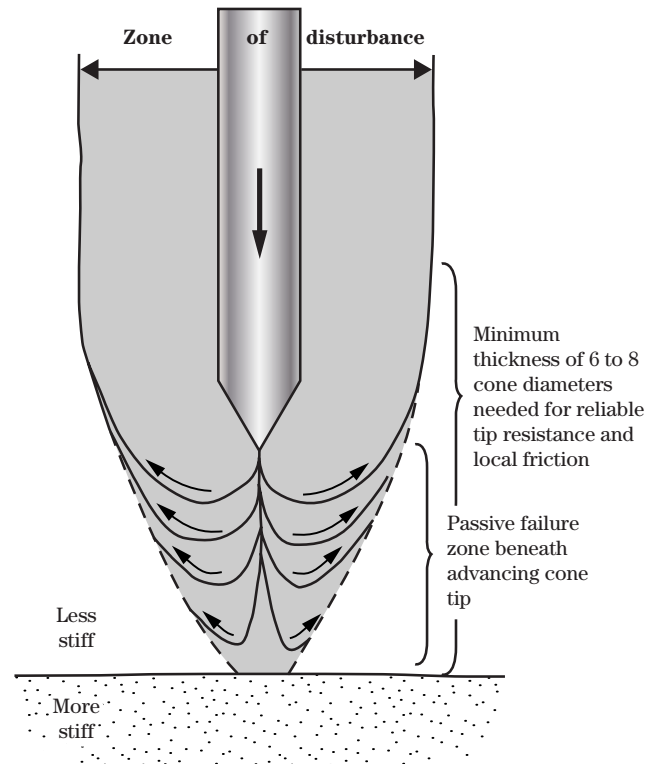
### 631.1103 Advantages, disadvantages, and cautions

The CPT was developed primarily for use in soft earth materials. The development of additional sensors and heavier equipment has extended the range of use. The advantages and disadvantages are shown in table 11–3.

The precise distance impacted below the cone tip depends on the stiffness and thickness of the units being penetrated and on the contrast in stiffness between adjacent beds (Rogers 2006; personal communication 2010). This influence varies between about 8 to 15 inches below the cone tip, so the soundings tend to overestimate unit strength parameters as the tip approaches a much stiffer horizon, such as the soil-bedrock contact (fig. 11–3).

The tip of the cone penetrometer senses out ahead of itself as it induces a local bearing failure of the soil through which it passes. The tip resistance recorded by the instrument is an average across this tip influence zone. Therefore, caution should be exercised when evaluating in situ strength parameters for horizons less than 14 to 28 inches (36–72 cm) thick, such as landslide slip surfaces (Rogers 2006).

**Figure 11–3** Zone of disturbance for cone penetrometer



## 631.1105 Equipment

A CPT system includes the following components (fig. 11-4):

- electronic penetrometer
- hydraulic pushing system with rods
- cable or transmission device
- depth recorder
- data acquisition unit

### (a) Penetrometers

The standard cone penetrometer consists of a three-channel-instrumented steel probe. The front end of the probe consists of a conical tip with a 60 degree apex. The tip typically has a 5-millimeter cylindrical extension, or lip, located at the upper portion to protect the outer edges of the cone base from excessive wear.

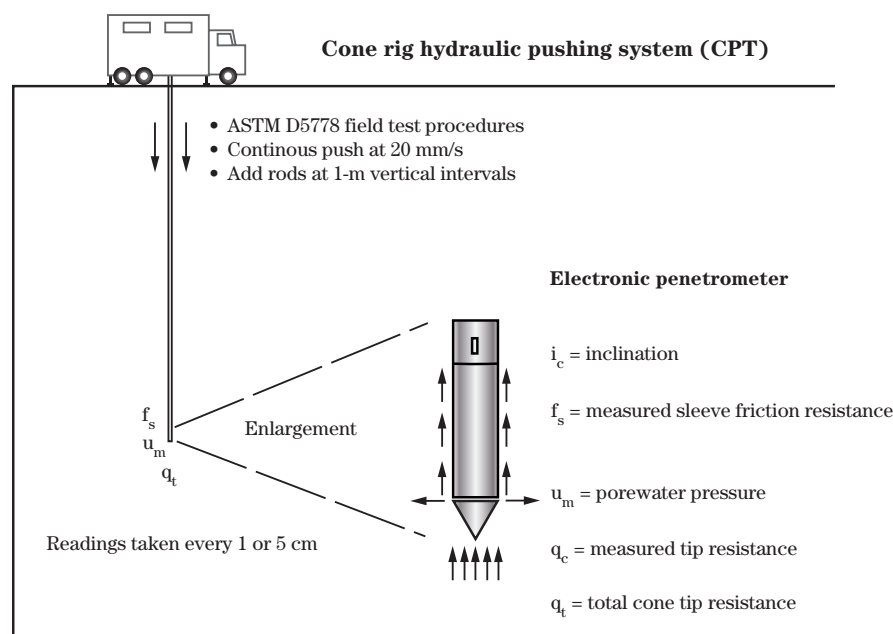
Penetrometers are normally available in two standard sizes:

- 35.7-millimeter diameter with a corresponding cross-sectional area of 10 square centimeters
- 44-millimeter diameter with a cross-sectional area of 15 square centimeters

The 10-square-centimeter size is the original standard size and remains in widespread use. However, the 15-square-centimeter version has some advantages and is specified in some standards. Being more robust, it can generally obtain soundings at greater depths and through coarser or harder materials. Also, as rods normally have a cross-sectional area of 10 square centimeters, the 44-millimeter-diameter cone produces a larger hole, reducing sleeve friction during pushing.

Figure 11-5 shows the basic styles of penetrometers in routine use. Detailed requirements and standards for the design, dimensions, and manufacturing and operating tolerances for the cone and sleeve are given in ASTM D5778.

**Figure 11-4** Configuration of the CPT, following ASTM D5778 (Mayne 2007, NCHRP Project 20-05)



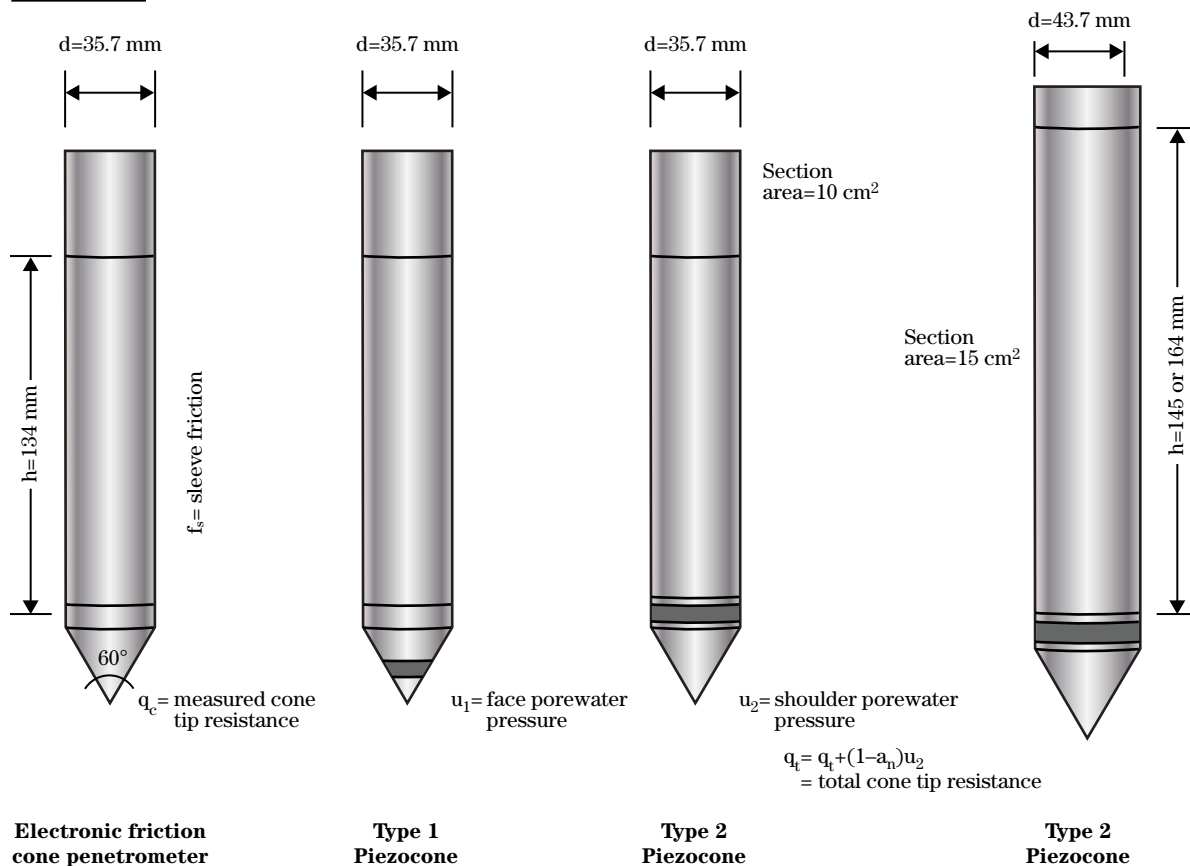
Cone penetrometers without porewater transducers can be used in soils with minor porewater pressure development, such as fill, clean sands, and soils well above the groundwater interface. However, for most soils below the water table, the piezocone penetrometer is recommended. It contains a porous filter element, pressure transducer, and fluid-filled ports connecting the element to the transducer. The filter element is usually positioned either at the apex or midface of the cone tip, or at the shoulder just behind the tip.

For the proper correction of measured cone tip resistance to total resistance, placement at the shoulder is required by national and international standards. Filter elements placed midface of the cone top are useful in fissured earth materials and other materials prone to desaturation.

The element is a fine porous filter made from plastic, ceramic, or sintered steel or bronze (formed by heating metal powders without melting). Typical pore size is between 20 and 200 microns. Different materials have unique properties that affect their suitability, including brittleness and durability, expense, and the ability to be cleaned and reused. Plastic filters are inexpensive, disposable, and can be replaced often to avoid possible clogging problems, particularly in plastic clays. Metal and ceramic filters are reusable and cleaned using an ultrasonic bath. Hydrophilic polypropylene elements placed at the shoulder are most commonly used in practice.

When using the cone to penetrate dense layers, such as cemented siltstone, sandstone, or conglomerate, a polypropylene piezo-filter can become compressed. This may induce high positive pore pressures. Plastic

**Figure 11-5** Dimensions and measurements taken by the standard 10-cm<sup>2</sup> and 15-cm<sup>2</sup> penetrometers, ASTM D5778



filters do not exhibit this tendency; however, they do become brittle with time and should be replaced periodically (Rogers 2006).

In stiff, overconsolidated clays, such as glacial till, the pore pressure is usually negative, and negative pore pressures may desaturate the cone, resulting in erroneous measurements. The pore pressure gradient around the cone can be high in these soils, resulting in dissipations recorded behind the tip that increase originally, and then decrease to the equilibrium value.

### (b) Hydraulic pushing systems

The hydraulic pushing machine can consist of the new dedicated CPT hydraulic system or a standard drill rig, mounted on a truck, track, trailer, all-terrain vehicle, skid arrangement, or portable unit. A variety of CPT systems are available, from mini units installed in vans used in shallow investigations, to large trucks and tracked vehicles useful for well-cemented or coarse-grained materials.

Standard drill rigs have the ability to drill or bore through hard zones and then continue the soundings to the desired depths, as well as to obtain soil samples. This greatly reduces costs associated with mobilizing a dedicated CPT truck.

Disadvantages of using a standard drill rig can include less thrust capabilities, the need for additional sub-connector pieces to advance and withdraw the rods, and manual controls, which depend on the operator and rarely push at a constant rate. A standard drill rig outfitted with CPT equipment is shown in figures 11-6 and 11-7.

Cone penetration soundings usually require thrust capabilities ranging from 100 to 200 kN, which is equivalent to 11 to 22 tons. After positioning the rig at the desired test location, the rig is usually leveled with hydraulic jacks or “outriggers.” Many small lightweight CPT systems in the 18- to 50-kN range (2- to 6- ton) use earth anchors to gain capacity and provide the necessary reaction for the penetrometer, as well as to prevent the rig from moving during thrust, relative to the soil surface.

**Figure 11-6** Drill rig set up to conduct SCPT. Metal plates are struck with a sledge hammer to initiate energy pulse. The seismic cone penetrometer has a geophone incorporated into its design. *(Photo courtesy of Glen Miller, Geologist (retired), NRCS, Stillwater, Oklahoma)*





**Figure 11-7** SCPT being conducted through hollow stem augers (Photo courtesy of Glen Miller, Geologist (retired), NRCS, Stillwater, Oklahoma)



### (c) Push rods

The push rods are typically 35.7-millimeter diameter, hollow, steel rods in 1-meter lengths with tapered threads. For hard materials, larger diameter cone rods (44 mm) are also available. Steel rods must have enough cross-sectional area to sustain, without buckling, the thrust required to advance the cone. For penetrometers using electrical cables, the cable is prestrung through the rods prior to testing. Hydraulic systems of dedicated CPT trucks are usually outfitted with grips to grasp the rods from the side during pushing and pulling. With standard drill rigs, pushing and pulling of rods is done from the top.

### (d) Friction reducer

Rod friction can be reduced through the use of a friction reducer, which is an enlarged section of rod (e.g., a ring welded to the outside rod) above the penetrometer that opens the hole to a larger diameter, thereby reducing soil contact on all the upper rods.

### (e) Data transmission and cabling

All analog and most digital CPT systems use a cable threaded through the rods that transmits the data uphole. It also provides between 5 to 20 volts of current to the penetrometer. The original analog systems require an external power supply, signal enhancer, and analog-digital converter at the surface.

Some of the newer designs include wireless digital CPT systems. They are useful when standard drill rigs are running the penetration equipment, as the cables can be easily damaged. They are used increasingly in deep-water offshore site investigations. Special receivers are required uphole to capture the signals and decode them for digital output. A variety of wireless technologies are available, including:

- infrared signals conveyed uphole in glass-lined rods
- audio signals
- battery-operated micro chips that store data until the rods are back at the surface

## (f) Depth loggers

Common systems for recording depth include depth wheels, low-voltage or direct current displacement transducers (LVDT and DCDT), gear boxes, optical readers, spooled wire potentiometers, and ultrasonic sensors, which use high-intensity acoustic energy. Spooled wire potentiometers consist of a transducer used to detect and measure the length of a moving object using a flexible cable and spring-loaded spool.

## (g) Data acquisition systems

Data acquisition systems used with electrical CPTs have evolved from simple pen plotters and analog-digital converters to laser printers. Now data are digitized to a computer at intervals that are typically 1 to 2 inches in depth. Fully digital systems include ruggedized notebook computers and microchip technologies built into the cone penetrometer itself.

Older systems can be adapted to almost any type of cone commercially available; however, most new systems have proprietary designs which require that the penetrometer, cable, and data acquisition system be matched.

## 631.1106 Standards

Procedures for calibrating and maintaining cone penetration equipment and for conducting CPTs are well-established. The following procedures are intended to contain the essential requirements for equipment, calibrations, and testing. Current ASTMs that are specific to individual systems are listed in table 11–4.

**Table 11–4** Applicable ASTM standards and standard guides for cone penetration testing

ASTM	Title
D3441	Standard Test Method for Mechanical Cone Penetration Tests of Soil
D5434	Standard Guide for Field Logging of Subsurface Explorations of Soil and Rock
D5753	Standard Guide for Planning and Conducting Borehole Geophysical Logging
D5778	Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils
D6066	Standard Practice for Determining the Normalized Penetration Resistance of Sands for Evaluation of Liquefaction Potential
D6067	Standard Guide for Using the Electronic Cone Penetrometer for Environmental Site Characterization

## 631.1107 Field operations—performing the CPT

Before setting up the rig, check for any safety hazards, including overhead utilities or obstructions. Local utility companies must be notified and their subsurface lines located and flagged. Such contact is normally required at least 24 to 48 hours in advance of the investigation. Soundings must not be performed any closer than 25-borehole diameters from any existing uncased or open boreholes.

### (a) Preparation for use of the penetrometer

Modern CPT equipment has the potential for producing results with a high degree of accuracy and repeatability. This accuracy depends on skilled operators and adequate facilities for calibration and maintenance of the equipment. Procedures and requirements for calibrating electronic penetrometers are described in the Annex to ASTM D5778. Simple calibrations and checks are also essential to ensure that everything is functioning properly in the field after connecting the equipment.

Electronic baselines or zero-load readings in both cone and friction sleeve load cells and porewater pressure transducers must be taken before and after each sounding. Baseline readings are a reliable indicator of output stability, temperature-induced apparent loads, soil ingress, internal friction, and threshold sensitivity. Also, they may indicate any unknown conditions that may be loading the system.

Baseline readings of the porewater pressure transducers should be obtained immediately after assembly to prevent evaporation at a temperature close to that of the material to be sounded. The penetrometer tip can hang freely in air or be immersed in a bucket of water. Baseline readings should not be obtained with protective caps or covers in place, as these may induce pressure in the system. It is also recommended to secure a set of baseline readings after the sounding has been completed, and the penetrometer withdrawn to the surface.

### (b) General procedures

For the soundings, the penetrometer thrust system of the CPT truck or drill rig must be set to as near vertical as possible. For penetration in compacted fills or hard soils, it may be necessary to prebore a hole through the upper material, using a diameter slightly larger than the cone. This will prevent damage to the cone. Before beginning the sounding, check individual push rods for straightness. Assemble and tighten push rods by hand, cleaning the threads if necessary to ensure that the shoulders are tightly butted to prevent damage to the rods.

The standard rate of push for CPT soundings is 2 centimeters per second (cm/s), usually applied in 1 meter increments, the length of a standard cone rod. With dedicated CPT rigs, the hydraulic system automatically adjusts the pressures to maintain a constant rate. When using a rotary drill rig, the driller must manually adjust the pressure to maintain the 2 centimeters per second rate. Cone results are generally not sensitive to slight variations in the rate of penetration.

As the rods are pushed, electrical cones produce continuous readings of cone resistance and sleeve friction. Electrical cones produce analog data, but most systems convert it to digital form at selected intervals. Most standards require the interval to be no more than 20 centimeters (~8 in); ASTM D5778 requires intervals not to exceed 5 centimeters (~2 in).

During testing, monitor the tip and sleeve forces continuously for signs of proper operation. As data are recorded, note any unusual occurrences in testing. These can include “crunching” sounds that may indicate gravel and directional drift of the penetrometer as it passes through or alongside obstructions such as boulders, cobbles, soil concretions, or thin rock layers. Inclination is a useful indicator of imminent danger to the system, as damage can be caused if resistant layers or obstructions are penetrated. Generally, a 5-degree change in inclination over 1 meter of penetration can result in rod bending.

As push rods are added, interruptions of short duration can affect initial cone and sleeve readings at the beginning of the next push. During a pause in the penetration, excess pore pressures will begin to dissipate. For that reason, it is important to note and record the



depths at which long pauses may have affected initial startup resistances.

At the end of the sounding, obtain a final set of baseline readings with the penetrometer tip hanging freely and check them against the initial readings. Maintain a continuous record of initial and final baselines for the tip and sleeve load cells and the porewater transducers, as they may indicate problems with the equipment.

Inspect penetrometer tips before and after soundings for damage, soil ingress, and wear. If soil ingress is significant, the cone assembly may need to be dismantled, cleaned, and lubricated before the next sounding.

### (c) Procedure for piezocone use

There are no major differences in field test procedures between CPT and CPTu, except those required for the preparation of a porous piezo-element, or filter, used in the latter (Robertson 1986). Before use, filters must be saturated under vacuum in a bath of glycerin, a mix of glycerin plus water, or peanut oil to remove compressible air bubbles which can cause errors in the soundings. In the field, the filter elements must be installed so that a continuity of fluid is maintained from the filter face through the ports in the penetrometer and the cavity housing the pressure transducer.

Caution should be used when interpreting CPT soundings above the water table. Unsaturated soils have negative pore pressures that can potentially distort the readings. They can also cause the development of air bubbles in the filter that can be suctioned off into the surrounding soils. Cohesive soils that are not fully saturated may exert significant skin friction, which can complicate the interpretation. In some geologic conditions, it may be necessary to prebore a pilot hole to the water table to obtain accurate porewater pressure readings in the saturated materials below.

### (d) Hole closure—techniques

The need for grouting or sealing of holes is usually established by individual States, most of which have laws requiring that exploration holes be backfilled, sealed, or grouted after sampling and testing are completed. The same applies to CPT sounding holes. This is of particular importance in specific geologic settings

where aquifer(s) need to be protected against cross-contamination or water transmission.

As the CPT cone is pushed into the ground, it is creating a hole that could be as detrimental to groundwater as an open borehole. If the hole stays open after the tool is withdrawn, these cavities can become pathways for contamination of aquifers either by cross-communication between permeable units or by the transport of surface contaminants down the hole. Surface and subsurface contaminants can potentially flow into aquifers that were previously uncontaminated.

Providing a permanent seal in small diameter holes presents a number of challenges compared with large-diameter holes drilled with a conventional drill rig. In larger-diameter holes, successful sealing can be performed using bentonite. In smaller diameter holes, it can be difficult or impossible to verify the seal's effectiveness due to the likelihood of bridging.

Specific geologic conditions may cause the holes to immediately close as the tool is removed. The best examples are relatively clean sands below the water table and very soft, saturated clays.

Borings in relatively clean, saturated sands are well known for unstable sidewalls that collapse during the drilling process. Drilling mud must be used to counteract this instability to keep the hole open. In loose deposits, the vibrations from the cone truck are enough to cause collapse during retraction. At the same time, the hydraulic conductivity in these deposits is likely to be several orders of magnitude above that of the sealing materials. For very soft clays below the water table, the hole may squeeze shut as the tools are being withdrawn. Suction that develops as the penetrometer is pulled from the hole increases this action.

## 631.1108 Field operations—readings and calculations

The two basic measurements taken during the test are tip resistance ( $q_c$ ) and sleeve friction ( $f_s$ ). Both  $q_c$  and  $f_s$  are determined by dividing the axial force by the surface area of the instrument (tip or sleeve). The axial force is represented by  $F$ .  $F_c$  is the axial force on the tip of the cone, while  $F_s$  is the axial force on the sleeve.

Cone tip resistance ( $q_c$ ) is the measured axial force pushing down on the tip, which is the force ( $F_c$ ) divided by the tip area ( $A_c$ ):

$$q_c = \frac{F_c}{A_c}$$

Sleeve resistance ( $f_s$ ) is the measured axial force pushing down on the sleeve ( $F_s$ ), divided by the sleeve area ( $A_s$ ):

$$f_s = \frac{F_s}{A_s}$$

### (a) Correcting tip and sleeve readings using porewater pressure ( $u_2$ )

Measured tip resistance ( $q_c$ ) must be adjusted to account for porewater pressures acting on unequal tip areas of the cone. In clean sands and dense, granular soils, they are nearly equivalent. However, in soft to stiff clayey soils, appreciable porewater pressures are generated, and the correction can be from 20 to 70 percent. Total tip resistance ( $q_t$ ) is calculated as:

$$q_t = q_c + (1 - a_n)u_2$$

where:

- $q_t$  = total tip resistance
- $a_n$  = tip net area ratio from triaxial test
- $q_c$  = measured tip resistance
- $u_2$  = porewater pressure at shoulder

The correction to total cone resistance is particularly important when porewater pressures are generated

during penetration; e.g., in saturated clays and silts, as weak soils are the most critical in a geotechnical investigation. The correction is usually not so significant for clean sands, dry soils, or dense to hard earth materials. The correction is due to porewater pressures acting on opposing sides of the face and the joint annulus of the tip (ASTM D5778).

The sleeve friction ( $f_s$ ) is also exposed to pore water pressures as well, which must be corrected. When excess pore pressures are generated, they are normally different at the upper ( $u_3$ ) and lower ( $u_2$ ) ends of the sleeve. The corrected sleeve friction ( $f_t$ ) is given by:

$$f_t = f_s - \left( \frac{u_2 \times A_{sh}}{A_s} \right) - \left( \frac{u_3 \times A_{st}}{A_s} \right)$$

where:

- $f_t$  = sleeve friction, corrected
- $f_s$  = sleeve friction
- $u_2$  = lower end of sleeve
- $u_3$  = upper end of sleeve
- $A_{sh}$  = bottom end area of sleeve
- $A_{st}$  = top end area of sleeve
- $A_s$  = area of sleeve

### (b) Field logging

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) standard logging procedures are outlined in NEH631.03. In particular, logs should contain:

- location and characteristics of contacts
- number of outer sounding tubes, as their weight can be an appreciable part of the record
- number of inner rods, to maintain the record of depth of penetration
- depth and length of long pauses in pushing
- initial and final baselines for each sounding
- any unusual condition affecting test procedures or results

## 631.1109 Soil mechanics laboratory use of CPT data

### (a) Soil classification

Where possible, soil classifications are to be based on the Visual-Manual Procedure outlined in ASTM D2488, Standard Practice for Description and Identification of Soils, and the appropriate laboratory test data. The CPT does not classify soils on their grain-size distribution, but provides a guide based on their mechanical characteristics or the soil behavior type. Some overlapping of zones can be expected. The SBT is derived from non-normalized data, which do not include pore pressure as do the newer CPT equipment and interpretation charts.

### (b) Determining extent of soils to be represented by sample testing

One of the most important and beneficial uses of CPT data in the laboratory is to provide a basis for judging whether engineering property test data can be accurately extended to represent soils located some distance from the sampling location. For example, in the slope stability analysis of an embankment, shear strength values determined using samples taken from the centerline of a structure are usually assumed to represent the foundation soils several hundred feet upstream and downstream. CPT data can be used to judge the extent of the area to which these data apply or indicate the need for further sampling and testing.

### (c) Consolidation and settlement testing and analysis

Undisturbed samples are seldom obtained from the center of a particular layer of foundation soil. CPT data provide information for determining more precisely the upper and lower boundaries represented by one or more samples. Engineering properties are not always uniform in earth materials of a given formation or geologic age.

A grouping of several cone tests at the base of an abutment can establish a reasonably accurate estimate of

potential differential settlements, which can then be confirmed by sampling and testing.

To compute horizontal strain associated with the design of principal spillway conduits, the lower limit of settlement must be known. Cone penetrometer tests extended to bedrock or to refusal in sands, gravels, or stiff clays provide good information for determining this lower limit. The reliability of samples, often obtained with great difficulty and expense, can then be judged for their potential use in settlement and strain analyses.

In areas where previous work has established a base of test results, analyses, and field measurements, settlement can be estimated using only CPT data if results of direct testing are not available. The general equation for consolidation of a layer ( $\Delta h$ ) is:

$$\Delta h = h \times \Delta p \times m_v$$

or

$$\Delta h = h \times \Delta p \times \left( \alpha \times \frac{1}{q_c} \right)$$

where:

$\Delta h$  = change in layer thickness, cm

$h$  = layer thickness, cm

$\Delta p$  = load; increase in vertical strength, kg/cm<sup>2</sup>

$\alpha$  = variable coefficient based on the state parameters of the soil

$q_c$  = cone point resistance, kgf/cm<sup>2</sup>

$m_v = \left( \alpha \times \frac{1}{q_c} \right)$ ; coefficient of mass volume change, cm<sup>3</sup>/kg

Using settlement plate data supported by laboratory testing, a graph of  $q_c$  vs.  $\alpha$  is computed for soils found in a given area:

$$\alpha = \frac{h \times \Delta p}{q_c \times \Delta h}$$

For fairly uniform soils and given adequate time,  $\Delta h$  from settlement plate records can be accurate for determining the  $\alpha$  coefficient. Compute the increase in stress due to the embankment load ( $\Delta p$ ) from field placement records. The graph is less accurate where the basis for computation is only laboratory testing to determine  $\Delta h$ .

### (d) Shear strength comparisons

Undrained shear strength values ( $S_u$  or cohesion,  $C_u$ ) are used in analyses of stability and bearing capacities for clays and clayey silts under short-term loadings. No single value of undrained shear strength of a given material exists, since the undrained response of a soil depends on the direction of loading, strain rate, boundary conditions, stress level, sample disturbance, and other factors.

While there is no single value of  $S_u$ , a relationship has been established between the undrained shear strength ( $S_u$ ) of a soil and a theoretical net cone resistance. Both theoretical and empirical solutions exist. The theoretical studies result in the following relationship between theoretical cone factor ( $N_c$ ) and in situ total pressure ( $\sigma_o$ ):

$$q_c = (N_c \times S_u) + \sigma_o$$

Empirical correlations are in a range of 10 to 20, with an average of 15.  $S_u$  is expressed as:

$$S_u = \frac{q_t - \sigma_t}{N_{kt}}$$

where:

- $q_t$  = total cone resistance
- $\sigma_t$  = vertical stress
- $N_{kt}$  = empirical cone factor

### (e) Slope stability analysis

Slip surfaces in landslides and other slope failures can be thin—less than 1 inch. CPT soundings are the best tool available to positively identify these low-strength horizons, which are otherwise difficult to sample, test, or measure reliably. In most cases, however, the soundings represent an average value of a zone that can be 8 to 15 inches thick.

In addition, the actual mobilized shear strength along the slip surface is usually considerably lower than the sleeve friction and tip resistance values recorded in the CPT, potentially as low as 20 percent of the estimated value (Rogers 2010, personal communication). Soundings are more definitive for thicker planes of weakness.

CPT results, coupled with results of laboratory shear testing, are useful in analyzing slope stability of foundation soils. Temperature sensors are also useful in assessing the precise position of the zone or zones of saturation, which is of great importance in slope stability and consolidation studies. A temperature shift of about 6 degrees Fahrenheit (3.3 °C) is common at the groundwater interface, even in perched water tables within landslides.

## 631.1110 Use of CPT data in design

### (a) Foundation

When determining the extent of excavation needed in fine-grained soils, compare results of representative laboratory consolidation and shear tests with CPT data. Tests on undisturbed samples usually represent a small volume of soil. In-place testing with the penetrometer allows the laboratory data to be applied to larger volumes of soil.

The CPT is a good tool for use during construction to determine if foundation excavation is completed and to locate soils of questionable properties not found in the predesign investigations. Construction specifications should allow the designer to use CPT or other in-place tests.

### (b) Sectional embankment or preloading

CPT can determine settlement at various points, where highly compressible soils extend to great depths. This information indicates that preloading the foundation soil or a sectional embankment is needed if settlement, differential settlement, or horizontal strain are potential problems. If preloading or a sectional embankment does not provide a solution to the potential problem, relocation of the structure may be required. Data from CPT can aid in locating soils of acceptable properties. Sampling and testing can then confirm the decision of structure location.

Data from CPT at locations of stilling basins and risers can confirm the results of laboratory tests on samples which are in many cases obtained only on the centerline of the structure.

### (c) Channels

Channel projects usually involve stratified soils and encompass long reaches. Use of the friction sleeve cone is accurate enough to classify the soils vertically and horizontally so that sampling may be more representative, and the investigation will also be faster and more economical. However, negative pore water pres-

ures in banks of influent streams cause an apparent cohesion that could skew results.

### (d) Liquefaction potential

CPT offers several capabilities in the evaluation of seismic ground hazards. The sounding can be used to identify loose, weak sands and silty sands below the groundwater interface that are susceptible to liquefaction. CPT data can also be used to determine the threshold for triggering liquefaction. Care should be taken to identify layers or zones of potential concern. Samples should be taken for fine-content testing to aid in the analysis.

CPT soundings can also be used to provide an assessment of the amount of resistance available to counter the shearing of the soil during ground shaking. The penetrometer can also be fitted with geophones to allow for the determination of downhole shear wave velocity profiles.

Liquefaction potential has traditionally been determined by the use of the Standard Penetration Test (SPT). Today, liquefaction potential is increasingly estimated based directly on the CPT (e.g., Youd et al. 2001; Robertson 2010, personal communication) because the CPT provides a continuous profile that is more reliable.

631.1111 SPT

Use of the SPT is presented in NEH631.04. The test provides a measure of earth material strength and also provides a representative sample of the horizon tested.

SPT advantages and disadvantages over CPT

Caution must be used in sampling geologic contacts and interpreting materials interfaces; as with the CPT there is an increase in the resistance to penetration as the drive sampler barrel approaches a stiffness boundary.

A major disadvantage of the SPT method is the small diameter of the cutting shoe. The equipment cannot recover clasts over 1.375 inches in diameter, which often leads to erroneous interpretations about bedrock contacts or drilling refusal.

SPT and CPT procedures work best when used together, not one exclusive of the other. The best correlations can be made when CPT soundings are verified with a SPT hole nearby (2 feet is a good distance). Use of the CPT allows detailed examinations of site stratigraphy. Individual beds and stringers can be traced across a sizable area in a minimal amount of time. In addition, the cone is able to delineate discrete, low-strength horizons that can be missed in a SPT sampler.

Robertson, Campanella, and Wightman (1983) summarized correlations between CPT cone penetration resistance and the SPT N value (blow count) and found that a relationship applies with an average energy ratio of about 60 percent; i.e.,  $N_{60}$ .

The  $(q_c/p_a)/N_{60}$  ratio correlates to the mean particle size of the soil ( $D_{50}$ ), where  $p_a$  is the atmospheric pressure in the same units as  $q_c$  (fig. 11–8). Table 11–5 relates this ratio to the soil behavior types (SBT). Values of  $q_c$  are made dimensionless when dividing by the atmospheric pressure ( $p_a$ ) in the same units as  $q_c$ . These ratios are a reasonable estimate, but discontinuous changes in the predicted SPT  $N_{60}$  values may occur. Note for sandy soils that the measured tip resistance ( $q_c$ ) = the total tip resistance ( $q_t$ ).

Figure 11–8 CPT–SPT correlations with mean grain size (Robertson, Campanella, and Wightman 1983)

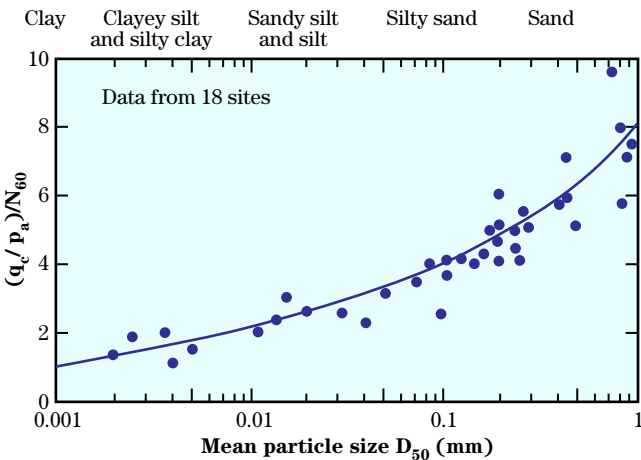


Table 11–5 Soil type correlating between CPT and SPT (Robertson 1986)

Zone	Soil behavior type *	$\left(\frac{q_s}{p_a}\right)$
		$N_{60}$
1	Sensitive fine grained	2.0
2	Organic soils—clay	1.0
3	Clays: clay to silty clay	1.5
4	Silt mixtures: clayey silt and silty clay	2.0
5	Sand mixtures: silty sand to sandy silt	3.0
6	Sands: clean sands to silty sands	5.0
7	Dense sand to gravelly sand	6.0
8	Very stiff sand to clayey sand	5.0
9	Very stiff fine-grained	1.0

\* Suggested  $(q_c/p_a)/N_{60}$  ratios

## 631.1112 Glossary

$A_c$	Projected area of cone
$a_n$	Tip net area ratio from triaxial test
$A_s$	Area of sleeve
$b_n$	Sleeve net ratio from triaxial test on the equipment itself, used to calibrate new equipment
$f_s$	Sleeve friction measured
$f_t$	Total sleeve friction, calculated
$F$	Total axial force acting on the instrument
$F_c$	Total force acting on the tip of the cone, $f_s/A_c$
$F_s$	Total force acting on friction sleeve, $f_s/A_s$
$N_c$	Theoretical cone resistance factor
$N_{kt}$	Empirically derived cone resistance factor
$p_a$	Atmospheric pressure
$R_f$	Friction ratio, $f_s/q_t$
$q_c$	Measured tip resistance
$q_t$	Total tip resistance
$u_m$	Measured penetration porewater pressure
$u$	Penetration pore water pressure
$u_1$	Porewater pressure at face
$u_2$	Porewater pressure at shoulder
CPT	Cone Penetrometer Test, can be performed with mechanical and electrical equipment
CPTu	Piezocone Penetration Test, can only be performed with electrical equipment
CPT $\dot{u}$	Piezocone with dissipation
SCPTu	Seismic Piezocone Penetration Test, equipment includes imbedded geophones that measure shear wave velocity
RCPTu	Resistivity Piezocone Penetration Test
$S_u = C_u$	Undrained shear strength
$S_t$	Soil sensitivity, the ratio of undisturbed, undrained shear strength to totally remolded, undrained shear strength
$\tau_f$	Shear strength, kgf/cm <sup>2</sup>
$\sigma_o$	Total in situ pressure

## 631.1113 References

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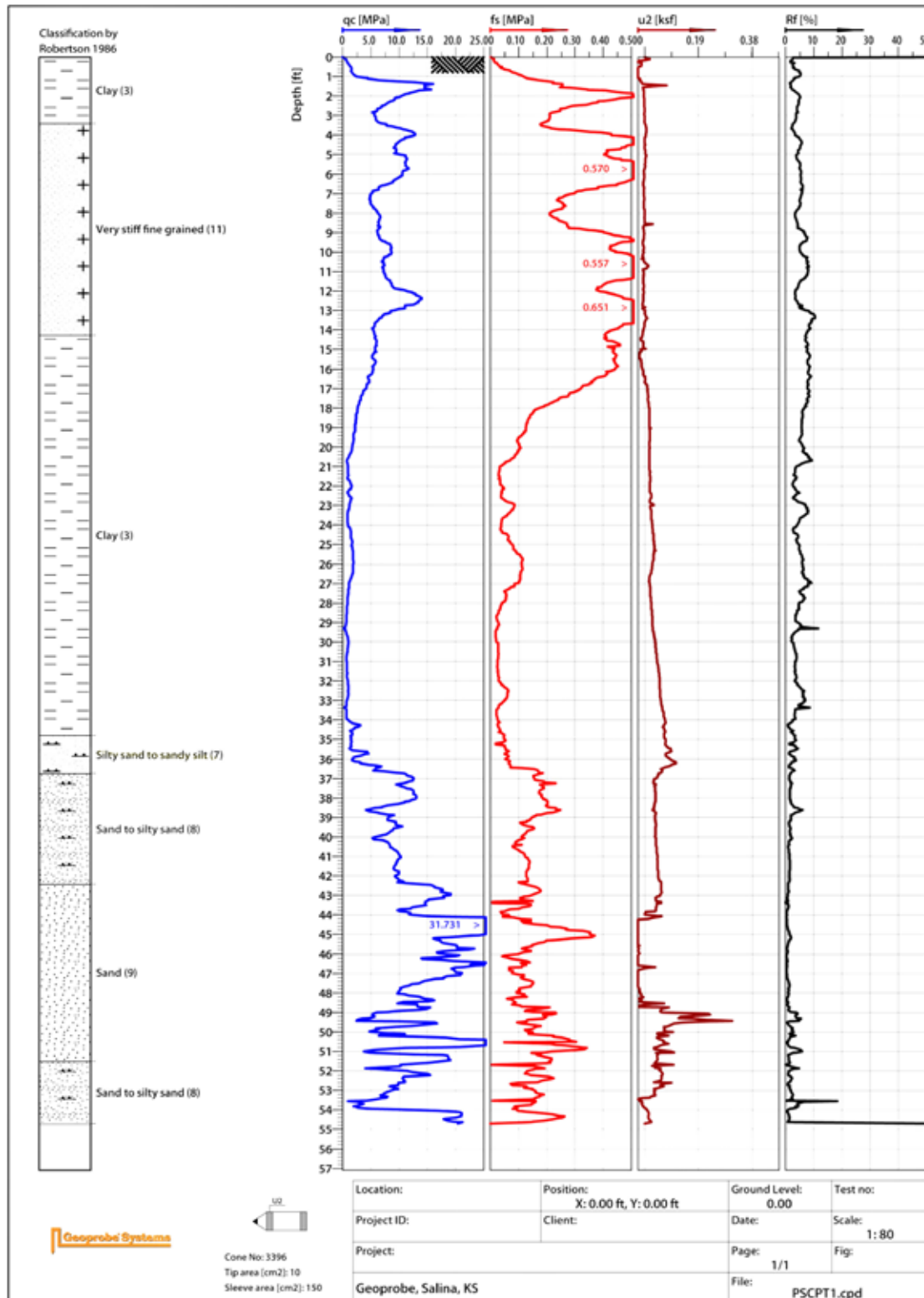




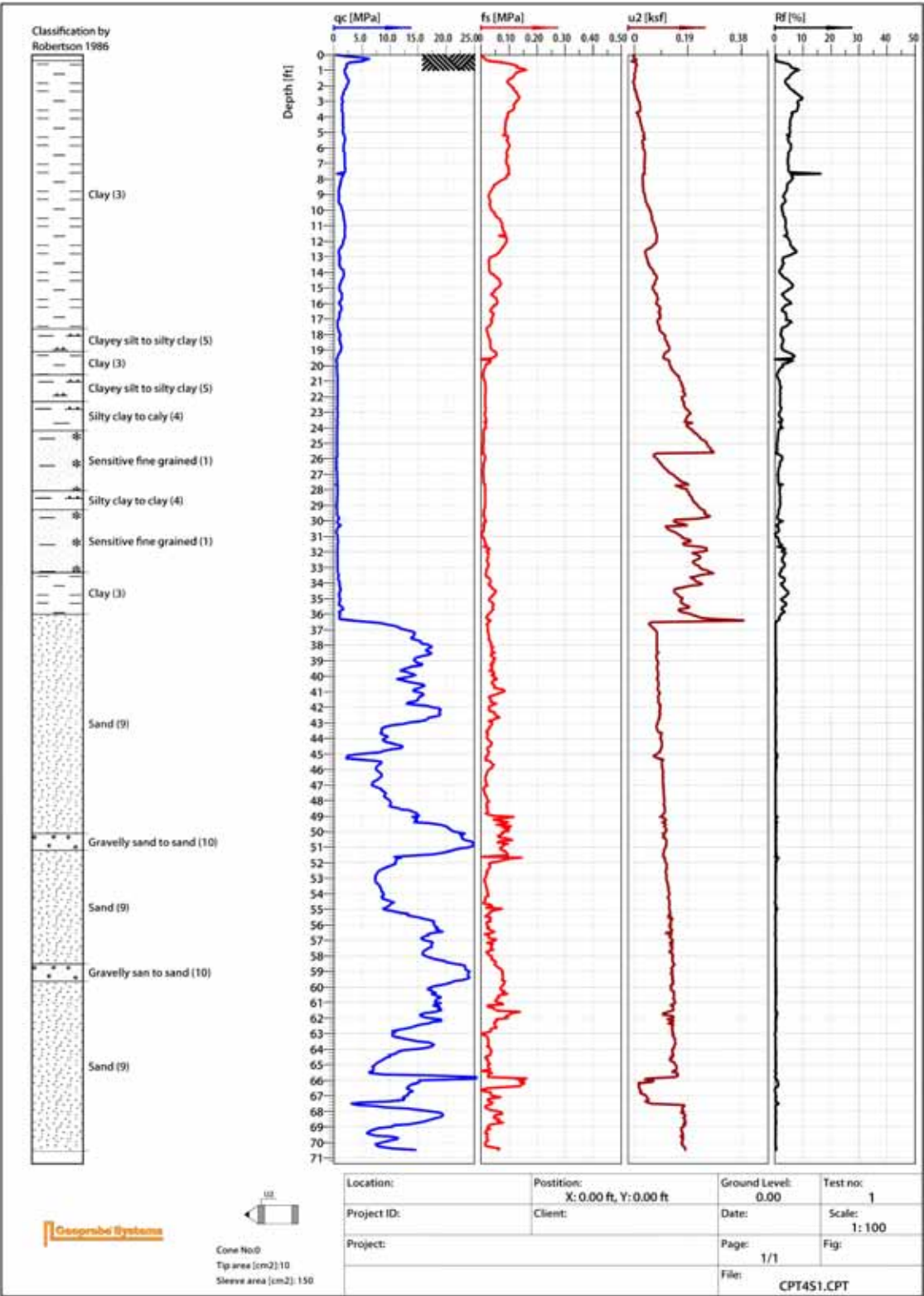
# Appendix A

# Examples of Cone Penetrometer Tests

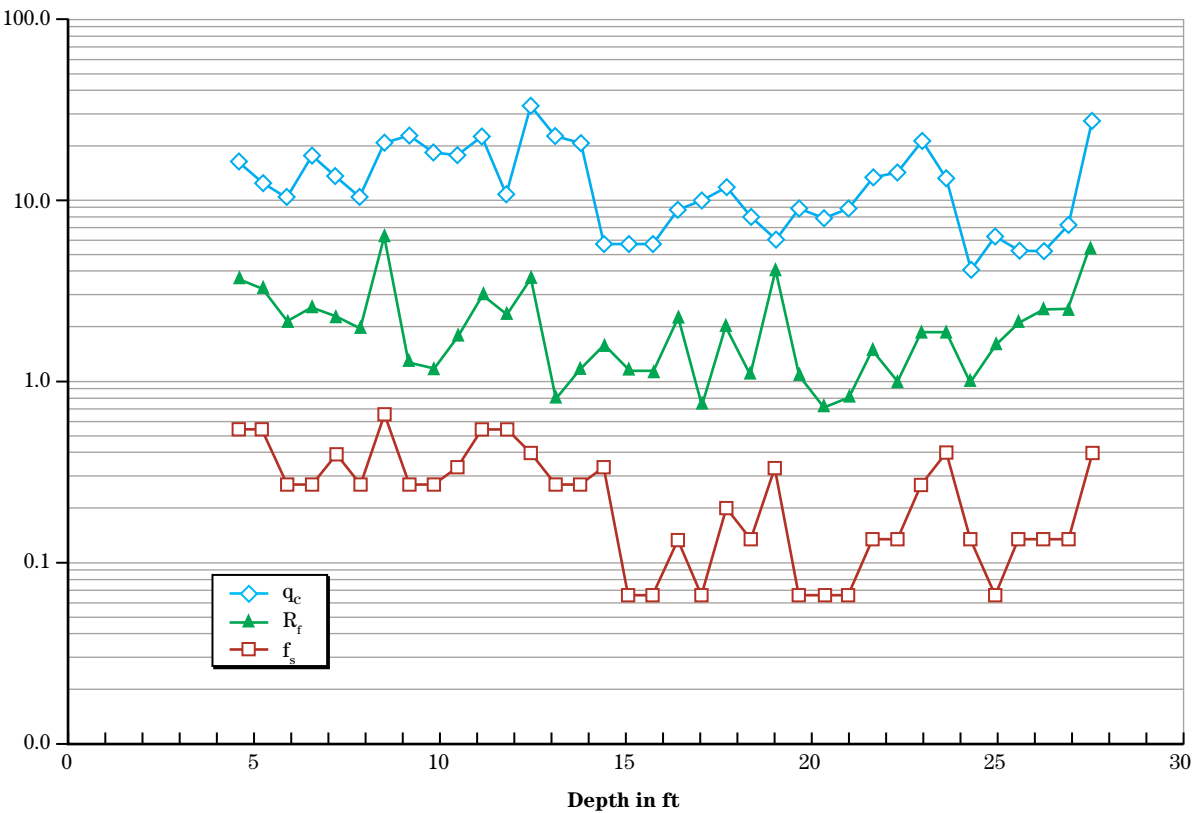
**Figure 11A-1** CPT log showing soil classification and soil behavior type, tip ( $q_c$ ), sleeve ( $f_s$ ), pore pressure ( $u_2$ ), and friction ratio ( $R_f$ ). Log clearly shows the varying soil conditions found when pushing CPT in Salina County, Kansas. See figure 11-2 for soil behavior types



**Figure 11A-2** CPT log showing soil classification, tip ( $q_c$ ), sleeve ( $f_s$ ), pore pressure ( $u_2$ ), and friction ratio ( $R_f$ ). Log clearly shows the change from clay to sand in both tip pressure and pore pressure. Note the steady increase in pore pressure beginning at 36 feet, indicating the probe had penetrated the water table.



**Figure 11A-3** Plot of CPT Data Record, Monroe County, Iowa



**Table 11A-1** CPT data record, Monroe Co., Iowa

Dutch Cone Soap Creek 4-86 DG=P <sub>2</sub> -P <sub>1</sub>		Monroe Co., IA $q_c = 0.14 \times (\# \text{ rods}) + 2 \times P_1$		10/5/2005 $f_s = 0.133 \times DG$		TH-2 $R_f = \frac{f_s}{q_c} \times 100$ (q <sub>c</sub> = previous reading)		W.L.=12.2
Depth (meters)	Depth (feet)	# rods	P <sub>1</sub>	P <sub>2</sub>	DG	q <sub>c</sub>	f <sub>s</sub>	R <sub>f</sub>
0.2	0.66							
0.4	1.31							
0.6	1.97							
0.8	2.62							
1	3.28							
1.2	3.94	2	7	8	1	14.3	0.1	#DIV/0!
1.4	4.59	2	8	12	4	16.3	0.5	3.7
1.6	5.25	3	6	10	4	12.4	0.5	3.3
1.8	5.90	3	5	7	2	10.4	0.3	2.1
2	6.56	3	8.5	10.5	2	17.4	0.3	2.6
2.2	7.22	3	6.5	9.5	3	13.4	0.4	2.3
2.4	7.87	3	5	7	2	10.4	0.3	2.0
2.6	8.53	4	10	15	5	20.6	0.7	6.4
2.8	9.18	4	11	13	2	22.6	0.3	1.3
3	9.84	4	9	11	2	18.6	0.3	1.2
3.2	10.50	4	8.5	11	2.5	17.6	0.3	1.8
3.4	11.15	4	11	15	4	22.6	0.5	3.0
3.6	11.81	5	11	15	4	10.7	0.5	2.4
3.8	12.46	5	16	19	3	32.7	0.4	3.7
4	13.12	5	11	13	2	22.7	0.3	0.8
4.2	13.78	5	10	12	2	20.7	0.3	1.2
4.4	14.43	5	2.5	5	2.5	5.7	0.3	1.6
4.6	15.09	6	2.5	3	0.5	5.8	0.1	1.2
4.8	15.74	6	2.5	3	0.5	5.8	0.1	1.1
5	16.40	6	4	5	1	8.8	0.1	2.3
5.2	17.06	6	4.5	5	0.5	9.8	0.1	0.8
5.4	17.71	6	5.5	7	1.5	11.8	0.2	2.0
5.6	18.37	7	3.5	4.5	1	8.0	0.1	1.1
5.8	19.02	7	2.5	5	2.5	6.0	0.3	4.2
6	19.68	7	4	4.5	0.5	9.0	0.1	1.1
6.2	20.34	7	3.5	4	0.5	8.0	0.1	0.7
6.4	20.99	7	4	4.5	0.5	9.0	0.1	0.8
6.6	21.65	8	6	7	1	13.1	0.1	1.5

**Table 11A-1** CPT data record, Monroe Co., Iowa—continued

Dutch Cone Soap Creek 4-86 DG=P <sub>2</sub> -P <sub>1</sub>		Monroe Co., IA			10/5/2005	TH-2	W.L.=12.2	
		$q_c = 0.14 \times (\# \text{ rods}) + 2 \times P_1$			$f_s = 0.133 \times DG$	$R_f = \frac{f_s}{q_c} \times 100$		
						(q <sub>c</sub> = previous reading)		
Depth (meters)	Depth (feet)	# rods	P <sub>1</sub>	P <sub>2</sub>	DG	q <sub>c</sub>	f <sub>s</sub>	R <sub>f</sub>
6.8	22.30	8	6.5	7.5	1	14.1	0.1	1.0
7	22.96	8	10	12	2	21.1	0.3	1.9
7.2	23.62	8	6	9	3	13.1	0.4	1.9
7.4	24.27	8	1.5	2.5	1	4.1	0.1	1.0
7.6	24.93	9	2.5	3	0.5	6.3	0.1	1.6
7.8	25.58	9	2	3	1	5.3	0.1	2.1
8	26.24	9	2	3	1	5.3	0.1	2.5
8.2	26.90	9	3	4	1	7.3	0.1	2.5
8.4	27.55	9	13	16	3	27.3	0.4	5.5



# Exhibit F



# California Well Standards



Water wells

Monitoring wells

Cathodic protection wells



California  
Department  
of Water Resources

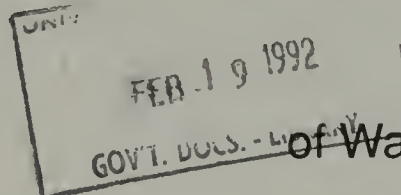
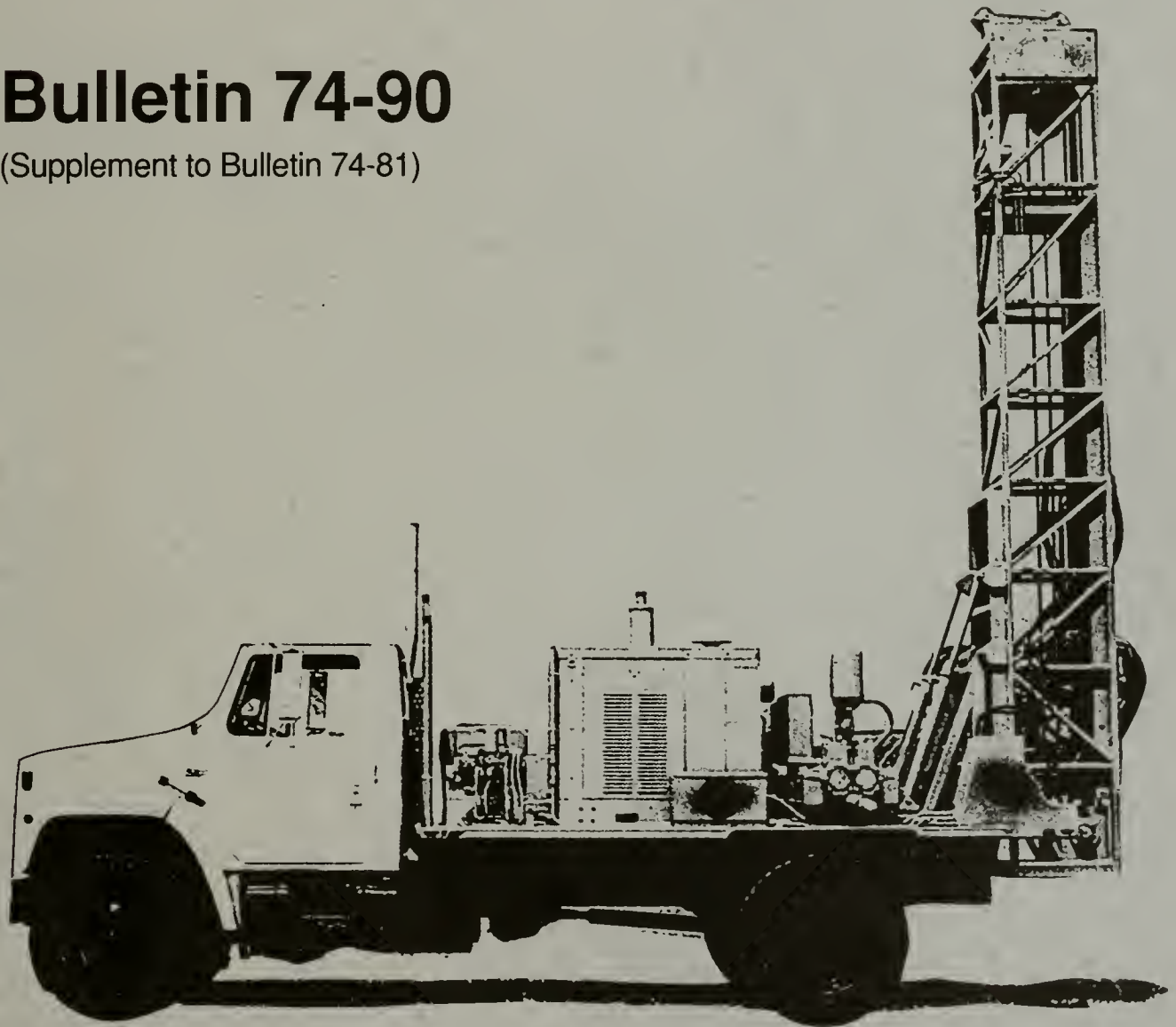


# California Well Standards

Water wells • Monitoring wells • Cathodic protection wells

## Bulletin 74-90

(Supplement to Bulletin 74-81)



California  
Department  
of Water Resources  
June 1991

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# Notice

This Bulletin is temporarily considered to be a draft. The California Department of Water Resources plans to adopt this Bulletin as final after a public review and comment period. The Department will announce in the future when this Bulletin is final. The Department will also announce any changes to this Bulletin. Announcement will be made through the Department's well standards mailing list.

This page should be removed from this Bulletin when it is announced that the Bulletin has been approved as final.

# • California Well Standards

Water wells • Monitoring wells • Cathodic protection wells

## Bulletin 74-90

(Supplement to Bulletin 74-81)

**David N. Kennedy**

Director  
Department of Water Resources

**Douglas P. Wheeler**

Secretary for Resources  
The Resources Agency

**Pete Wilson**

Governor  
State of California



California  
Department  
of Water Resources  
June 1991

## FOREWORD

During an average year about forty percent of California's water supply comes from ground water. Ground water is used for agricultural, industrial, domestic, and municipal water supplies. Protecting the quality of California's ground water is essential to California's future.

Improperly constructed wells can allow pollution of ground water to the point that the water is either unusable or it requires expensive treatment. The California Water Code requires the Department of Water Resources (DWR) to develop minimum standards for water wells, monitoring wells, and cathodic protection wells to protect ground water quality.

This bulletin is a supplement to DWR Bulletin 74-81, *Water Well Standards: State of California, December 1981*. Standards in Bulletin 74-81 and this bulletin are **minimum** requirements for construction, alteration, maintenance, and destruction of water wells, monitoring wells, and cathodic protection wells in California.

This bulletin was prepared in cooperation with the State Water Resources Control Board. The Board adopted a model water well, monitoring well, and cathodic protection well ordinance that implements DWR well standards. All California cities and counties, and some water agencies are required to enact local well ordinances that meet or exceed DWR standards, or they must enforce the Board's model ordinance as if it were their own.

Sometimes well standards adopted by local agencies must be more stringent than DWR's statewide standards because of local conditions. Local agencies play a critical role in protecting ground water quality.

Continued cooperation is needed between the public, industry, local agencies, and the State to ensure that these well standards remain adequate and are put into practice. California's water supply future depends on this cooperation.

David N. Kennedy, Director  
Department of Water Resources



State of California  
**PETE WILSON**, Governor

The Resources Agency  
**DOUGLAS P. WHEELER**, Secretary for Resources

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The CALIFORNIA WATER COMMISSION serves as a policy advisory body to the Director of the Department of Water Resources on all California water resource matters. The nine-member citizen commission provides a water resources forum for the people of the State, acts as liaison between the legislative and executive branches of State government, and coordinates federal, State, and local water resources efforts.

# CALIFORNIA WELL STANDARDS

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## ACKNOWLEDGEMENTS

This bulletin was prepared after consideration of comments and suggestions from public agencies and private parties. State agencies that provided input include:

- State Water Resources Control Board,
- Regional Water Quality Control Boards,
- Department of Health Services, and,
- California Integrated Waste Management Board.

Many comments and suggestions were received from California cities, counties, and water agencies. Private parties that provided input include the California Groundwater Association, individual well contractors, well construction material and equipment suppliers, and consultants. The Department of Water Resources thanks all persons that provided comments during the preparation of this bulletin.

# GENERAL INTRODUCTION

## GENERAL INTRODUCTION

Improperly constructed, altered, maintained, or destroyed wells are a potential pathway for introducing poor quality water, pollutants, and contaminants to good-quality ground water. The potential for ground water quality degradation increases as the number of wells and borings in an area increases.

Improperly constructed, altered, maintained, or destroyed wells can facilitate ground water quality degradation by allowing:

- Pollutants, contaminants, and water to enter a well bore or casing;
- Poor quality surface and subsurface water, pollutants, and contaminants to move between the casing and borehole wall;
- Poor quality ground water, pollutants, and contaminants to move from one stratum or aquifer to another; and,
- The well bore to be used for illegal waste disposal.

Permanently inactive or "abandoned" wells that have not been properly destroyed pose a serious threat to water quality. They are frequently forgotten and become dilapidated with time, and thus can become conduits for ground water quality degradation. In addition, humans and animals can fall into wells left open at the surface.

## History of DWR Standards

The Department of Water Resources has responsibility for developing standards for wells for the protection of water quality under California Water Code Section 231. Water Code Section 231 was enacted in 1949.

Statewide standards for water wells were first formally published in 1968 as DWR Bulletin 74, *Water Well Standards: State of California*. Standards for cathodic protection wells followed in 1973 as Bulletin 74-1, *Cathodic Protection Well Standards: State of California*. Bulletins 74 and 74-1 are now out of print.

A revised edition of Bulletin 74 was published in 1981 as Bulletin 74-81 *Water Well Standards: State of California*. Bulletin 74-81 is enclosed in the back cover of this report.

The law for establishing and implementing well standards was changed significantly in 1986 by Assembly Bill 3127 and Senate Bill 1817 (now Chapters 1152 and 1373, Statutes of 1986). Assembly Bill 3127 (Water Code Section 13801) requires that:

- (1) By September 1, 1989, the State Water Resources Control Board adopt a model well ordinance implementing DWR standards.
- (2) By January 15, 1990, all counties and cities, and water agencies where appropriate, adopt a well ordinance that meets or exceeds DWR well standards.
- (3) By February 15, 1990, the Board's model ordinance is to be enforced by any county, city, or water agency failing to adopt a well ordinance.

Senate Bill 1817 amended the Water Code to specifically include monitoring wells. It was previously assumed that monitoring wells were included in the collective term "well" used in the law.

As a first step in carrying out provisions of the amended law, the State Water Resources Control Board contracted with DWR to:

- (1) Review and update water well standards in Bulletin 74-81;
- (2) Establish minimum standards for monitoring wells; and,
- (3) Update and replace cathodic protection well standards in Bulletin 74-1.

This Bulletin is a supplement to Bulletin 74-81. It was developed to satisfy the Department's contract with SWRCB, to respond to Department responsibilities under the Water Code, and to keep pace with technical advances during the ten-year period following publication of Bulletin 74-81.

An initial draft of this supplement was published in three sections and was sent to interested organizations and individuals for comment during the Fall of 1988. The Department held public hearings in Los Angeles, November 15, 1988 and in Oakland, November 17, 1988 to discuss the draft supplemental standards and receive public comment.

Several sets of written comments for the draft supplemental standards were received by DWR. Written and verbal comments on the standards were reviewed and appropriate changes were incorporated into *Final Draft Bulletin 74-90, California Well Standards; Water Wells, Monitoring Wells, Cathodic Protection Wells; Supplement to Bulletin 74-81*, January 1990.

*Final Draft Bulletin 74-90* was published in November 1989 and was sent to interested organizations and individuals for comment. Comments were reviewed and appropriate changes were incorporated into this final bulletin.

Additional discussion on the history of DWR well standards is contained in Bulletin 74-81.

### **Relationship of DWR Well Standards Publications**

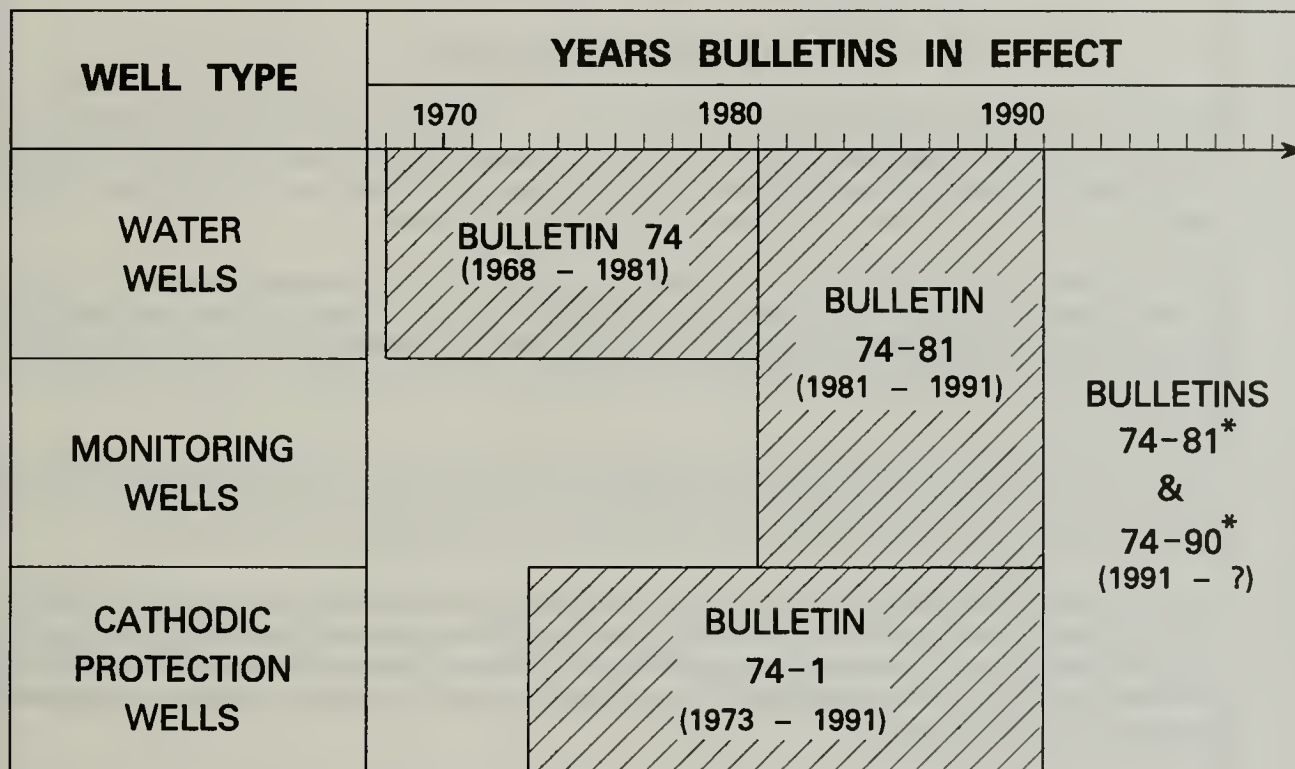
DWR Bulletins 74-81 and 74-1 provided the Department's standards for water wells and cathodic protection wells just prior to this supplement. DWR standards for monitoring wells were generally the same as for water wells prior to this supplement and were included in Bulletin 74-81. The relationship of the various DWR well standards bulletins is illustrated in Figure 1.

Revised standards for water wells in this supplement replace only portions of the water well standards contained in Bulletin 74-81. This supplement is to be used together with Bulletin 74-81 for a complete description of DWR Water Well Standards.

Monitoring well standards are presented separately in this supplement and are in parallel form to the water well standards. Because many physical similarities exist between water wells and monitoring wells, the water well standards are referred to frequently in the monitoring well standards. Water well and monitoring well standards must be considered together for the construction, alteration, maintenance, and destruction of monitoring wells.

Cathodic protection well standards in this supplement replace those in Bulletin 74-1. Because of similarities between cathodic protection wells and water wells, water wells standards are referred to frequently in the cathodic protection well standards. Cathodic protection well standards and water well standards must be considered together for the construction, alteration, maintenance, and destruction of cathodic protection wells.

**Figure 1. YEARS DWR WELL STANDARDS  
BULLETINS IN EFFECT**



\* Both bulletins are now required for water well, monitoring well, and cathodic protection well standards.



## Organization of This Supplement

Standards in this supplement are presented in three parts:

- (1) Revisions of some water well standards in Bulletin 74-81.
- (2) Standards for monitoring wells.
- (3) Updated standards for cathodic protection wells that were originally published in Bulletin 74-1.

Selected technical terms used in this supplement are listed and defined in Appendix A. A list of references is contained in Appendix B.

## Limitations of Standards

Well standards contained in Bulletin 74-81 together with well standards in this supplement (Bulletin 74-90) are recommended *minimum* statewide standards for the protection of ground water quality. *The standards are not necessarily sufficient for local conditions.* Local enforcing agencies may need to adopt more stringent standards for local conditions to ensure ground water quality protection.

In some cases, it may be necessary for a local enforcing agency to substitute alternate measures or standards to provide protection equal to that otherwise afforded by DWR standards. Such cases arise from practicalities in applying standards, and from variations in geologic and hydrologic conditions. Because it is impractical to prepare "site-specific" standards covering every conceivable case, provision has been made for deviation from the standards.

Standards in Bulletin 74-81 and this supplement (Bulletin 74-90) *do not ensure* proper construction or function of any type of well. Proper well design and construction practices require the use of these standards together with accepted industry practices, regulatory requirements, and consideration of site conditions.

*It is the ultimate responsibility of the well owner and/or the owner's technical and/or contractor representative(s) to ensure that a well does not constitute a significant pathway for the movement of poor-quality water, pollutants, or contaminants; does not constitute a public nuisance or hazard; and, adequately performs a desired function. The Department accepts no responsibility for improper design, construction, alteration, maintenance, function, or destruction of individual wells.*

## Applicability

Construction standards presented in this supplement apply to all water wells, monitoring wells, and cathodic protection wells constructed after the date of this supplement. Alteration, maintenance, and destruction standards presented in this supplement apply to all water wells, monitoring wells, cathodic protection wells, and "borings" regardless of their original date of construction. Standards contained in Bulletin 74-81 remain in effect except where modified by this supplement (Bulletin 74-90).

# WATER WELLS

# REVISIONS TO WATER WELL STANDARDS

## INTRODUCTION

Revisions to standards in DWR Bulletin 74-81, Chapter II, are presented in this section. All standards in Bulletin 74-81 that are not revised by this supplement (Bulletin 74-90) remain unchanged and in effect. The organization and numbering system used for the revisions is the same as that in Bulletin 74-81.

Table 1, page 10, below, lists portions of Bulletin 74-81 that are replaced by this supplement (Bulletin 74-90). The user of this supplement should strike-out the replaced sections and paragraphs in the copy of Bulletin 74-81 that is enclosed in the back cover of this supplement.



Table 1

**Deletions in Bulletin 74-81**

<b>Page</b>	<b>Portions of Bulletin 74-81 Replaced by this Supplement, Bulletin 74-90</b>
24	Subsection I
25	Subsections J and L
26	Subsection A of Section 8, and Footnote No. 3
27	Entire Page, Including All Footnotes
29	Entire Page, Including All Footnotes
30	Entire Page, Including All Footnotes
32	Remainder of Item 3
34	Subsection D, and All Footnotes
35	Entire Page, Including All Footnotes
36	Item 2, Item 3, and Item 4
39	Item 5, Subsection B, and All Footnotes
40	Subsection F, and Footnote No. 1
43	Item 3, and Footnote No. 1
44	Remainder of Item 3, and Both Footnotes
45	Item 5, and Item 6, Subsection B, and Both Footnotes
46	Remainder of Subsection B, Section 14
48	Remainder of Section 14
52	Section 21, Footnote No. 2
53	Remainder of Section 21, Item 1
54	Item 1

## STANDARDS

### Part I. General

#### Section 1. Definitions.

Definitions A through H, and K (page 23 of Bulletin 74-81) are unchanged. The definition for observation and monitoring wells under Definition I has been deleted and replaced with a definition for "exploration hole." Observation or monitoring wells are now addressed in monitoring well standards in this supplement.

The new definition under Definition I is:

- "I. Exploration Hole (or Boring). An uncased, temporary excavation whose purpose is the determination of hydrologic conditions at a site."

Definitions J and L have been revised to read as follows:

- "J. Test Wells. Wells constructed to obtain information needed for design of other wells. Test wells should not be confused with "exploration holes", which are temporary. Test wells are cased and can be converted to other uses such as ground water monitoring and, under certain circumstances, to production wells.
- L. Enforcing Agency. An agency designated by duly authorized local, regional, or State government to administer and enforce laws or ordinances pertaining to the construction, alteration, maintenance, and destruction of water wells. The California State Department of Health Services or the local health agency is the enforcing agency for community water supply wells."

Sections 2 through 7 (page 25 of Bulletin 74-81) are unchanged.

## Part II. Well Construction

### Section 8. Well Location With Respect to Pollutants and Contaminants, and Structures.

**Note:** The title of Section 8 has been revised.

Section 8 (page 26 of Bulletin 74-81) has been revised to read as follows:

"A. Separation. All water wells shall be located an adequate horizontal distance from known or potential sources of pollution and contamination. Such sources include, but are not limited to:

- sanitary, industrial, and storm sewers;
- septic tanks and leachfields;
- sewage and industrial waste ponds;
- barnyard and stable areas;
- feedlots;
- solid waste disposal sites;
- above and below ground tanks and pipelines for storage and conveyance of petroleum products or other chemicals; and,
- storage and preparation areas for pesticides, fertilizers, and other chemicals.

Consideration should also be given to adequate separation from sites or areas with known or suspected soil or water pollution or contamination.

The following horizontal separation distances are generally considered adequate where a significant layer of unsaturated, unconsolidated sediment less permeable than sand is encountered between ground surface and ground water. These distances are based on present knowledge and past experience. Local conditions may require greater separation distances to ensure ground water quality protection.

Potential Pollution or Contamination Source	Minimum Horizontal Separation Distance Between Well and Known or Potential Source
Any sewer line (sanitary, industrial, or storm; main or lateral)	50 feet
Watertight septic tank or subsurface sewage leaching field	100 feet
Cesspool or seepage pit	150 feet
Animal or fowl enclosure	100 feet

If the well is a radial collector well, minimum separation distances shall apply to the furthest extended point of the well.

Many variables are involved in determining the "safe" separation distance between a well and a potential source of pollution or contamination. No set separation distance is adequate and reasonable for all conditions. Determination of the safe separation distance for individual wells requires detailed evaluation of existing and future site conditions.

Where, in the opinion of the enforcing agency adverse conditions exist, the above separation distances shall be increased, or special means of protection, particularly in the construction of the well, shall be provided, such as increasing the length of the annular seal.

Lesser distances than those listed above may be acceptable where physical conditions preclude compliance with the specified minimum separation distances and where special means of protection are provided. Lesser separation distances must be approved by the enforcing agency on a case-by-case basis.

- B. Gradients. Where possible, a well shall be located up the ground water gradient from potential sources of pollution or contamination. Locating wells up gradient from pollutant and contaminant sources can provide an extra measure of protection for a well. However, consideration should be given that the gradient near a well can be reversed by pumping, as shown in Figure 3 (page 28 of Bulletin 74-81), or by other influences.
- C. Flooding and Drainage. If possible, a well should be located outside areas of flooding. The top of the well casing shall terminate above grade and above known levels of flooding caused by drainage or runoff from surrounding land. For community water supply wells, this level is defined as the:

"...floodplain of a 100 year flood..." or above "...any recorded high tide...",  
(Section 64417, *Siting Requirements*, Title 22 of the California Code of Regulations.)

If compliance with the casing height requirement for community water supply wells and other water wells is not practical, the enforcing agency shall require alternate means of protection.

Surface drainage from areas near the well shall be directed away from the well. If necessary, the area around the well shall be built up so that drainage moves away from the well.

- D. Accessibility. All wells shall be located an adequate distance from buildings and other structures to allow access for well modification, maintenance, repair, and destruction, unless otherwise approved by the enforcing agency."

## Section 9. Sealing the Upper Annular Space.

**Note:** Sealing requirements are also described in Appendix B, page 67 of Bulletin 74-81.

Section 9 (page 29 of Bulletin 74-81) has been revised to read as follows:

"The space between the well casing and the wall of the drilled hole, often referred to as the annular space, shall be effectively sealed to prevent it from being a preferential pathway for movement of poor-quality water, pollutants, or contaminants. In some cases, secondary purposes of an annular seal are to protect casing against corrosion or degradation, ensure the structural integrity of the casing, and stabilize the borehole wall.



- A. Minimum Depth of Annular Surface Seal. The annular surface seal for various types of water wells shall extend from ground surface to the following minimum depths:

Well Type	Minimum Depth Seal Must Extend Below Ground Surface
Community Water Supply	50 feet
Industrial	50 feet
Individual Domestic	20 feet
Agricultural	20 feet
Air-Conditioning	20 feet
All Other Types	20 feet

1. Shallow ground water. Exceptions to minimum seal depths can be made for shallow wells at the approval of the enforcing agency, where the water to be produced is at a depth less than 20 feet. In no case shall an annular seal extend to a total depth less than 10 feet below land surface. The annular seal shall be no less than 10 feet in length.

Caution shall be given to locating a well with a 'reduced' annular seal with respect to sources of pollution or contamination. Such precautions include horizontal separation distances greater than those listed in Section 8, page 12, above.

2. Encroachment on known or potential sources of pollution or contamination. When, at the approval of the enforcing agency, a water well is to be located closer to a source of pollution or contamination than allowed by Section 8, page 12, above, the annular space shall be sealed from ground surface to the first impervious stratum, if possible. The annular seal for all such wells shall extend to a minimum depth of 50 feet.
3. Areas of freezing. The top of an annular surface seal may be below ground surface in areas where freezing is likely, but in no case more than 4 feet below ground surface. 'Freezing' areas are those where the mean length of the freeze-free period described by the National Weather Service is less than 100 days. In other words, 'freezing' areas are where temperatures at or below 32 degrees Fahrenheit are likely to occur on any day during a period of 265 or more days each year. In general, these areas include:
  - portions of Modoc, Lassen, and Siskiyou Counties;
  - portions of the North Lahontan area including the eastern slope of the Sierra Nevada and related valleys north of Mount Whitney and Mono Lake; and,
  - the area of Lake Arrowhead in the San Bernardino Mountains.
4. Vaults. At the approval of the enforcing agency, the top of an annular surface seal and well casing can be below ground surface where traffic or other conditions require, if the seal and casing extend to a watertight and structurally sound subsurface vault, or equivalent feature. In no case shall the top of the annular surface seal be more

than 4 feet below ground surface. The vault shall extend from the top of the annular seal to at least ground surface.

The use of subsurface vaults to house the top of water wells below ground surface is rare and is discouraged due to susceptibility to the entrance of surface water, pollutants, and contaminants. Where appropriate, pitless adapters should be used in place of vaults.

B. Sealing Conditions. The following requirements are to be observed for sealing the annular space.

1. Wells drilled in unconsolidated, caving material. An 'oversized' hole, at least 4 inches greater in diameter than the outside diameter of the well casing, shall be drilled and a conductor casing temporarily installed to at least the minimum depth of annular seal specified in Subsection A, page 14, above. Permanent conductor casing may be used if it is installed in accordance with Item 3, page 16, below, and Item 5 (page 32 of Bulletin 74-81) and if it extends at least to the depth specified in Subsection A, above. One purpose of conductor casing is to hold the annular space open during well drilling and during the placement of the well casing and annular seal.

Temporary conductor casing shall be withdrawn as sealing material is placed between the well casing and borehole wall, as shown in Figure 4A (page 31 of Bulletin 74-81). Sealing material shall be placed at least within the interval specified in Subsection A, above. The sealing material shall be kept at a sufficient height above the bottom of the temporary conductor casing as it is withdrawn to prevent caving of the borehole wall.

Temporary conductor casing may be left in place in the borehole after the placement of the annular seal only if it is impossible to remove because of unforeseen conditions and not because of inadequate drilling equipment, or if its removal will seriously jeopardize the integrity of the well and the integrity of subsurface barriers to pollutant or contaminant movement. Temporary conductor casing may be left in place only at the approval of the enforcing agency on a case-by-case basis.

Every effort shall be made to place sealing material between the outside of temporary conductor casing that cannot be removed and the borehole wall to fill any possible gaps or voids between the conductor casing and the borehole wall. At least two inches of sealing material shall be maintained between the conductor casing and well casing. At a minimum, sealing material shall extend through intervals specified in Subsection A, above.

Sealing material can often be placed between temporary conductor casing that cannot be removed and the borehole wall by means of pressure grouting techniques, as described below and in Appendix B (page 67 of Bulletin 74-81). Other means of placing sealing material between the conductor casing and the borehole wall can be used, at the approval of the enforcing agency.

Pressure grouting shall be accomplished by perforating temporary conductor casing that cannot be removed, in place. The perforations are to provide passages for sealing material to pass through the conductor casing to fill any spaces and voids between the casing and borehole wall. Casing perforations shall be a suitable size and density to allow the passage of sealing materials through the casing and the proper distribution

of sealing material in spaces between the casing and borehole wall. At a minimum, the perforations shall extend through the intervals specified in Subsection A, above, unless otherwise approved by the enforcing agency.

Temporary conductor casing that must be left in place shall be perforated immediately before sealing operations begin to prevent drilling or well construction operations from clogging casing perforations. Once the casing has been adequately perforated, sealing material shall be placed inside the conductor casing and subjected to sufficient pressure to cause the sealing material to pass through the conductor casing perforations and completely fill any spaces or voids between the casing and borehole wall, at least within the intervals specified in Subsection A, above. Sealing material shall consist of neat cement, or bentonite prepared from powdered bentonite and water, unless otherwise approved by the enforcing agency.

Sealing material must also fill the annular space between the conductor casing and the well casing within required sealing intervals.

2. Wells drilled in unconsolidated material with significant clay layers. An 'oversized' hole, at least 4 inches greater in diameter than the outside diameter of the well casing, shall be drilled to at least the depth specified in Subsection A, page 14, above, and the annular space between the borehole wall and the well casing filled with sealing material in accordance with Subsection A, above (see Figure 4B, page 31 of Bulletin 74-81). If a significant layer of clay or clay-rich deposits of low permeability is encountered within 5 feet of the minimum seal depth prescribed in Subsection A, above, the annular seal shall be extended at least 5 feet into the clay layer. Thus, the depth of seal could be required to be extended as much as another 10 feet. If the clay layer is less than 5 feet in total thickness, the seal shall extend through its entire thickness.

If caving material is present within the interval specified in Subsection A, a temporary conductor casing shall be installed to hold the borehole open during well drilling and placement of the casing and annular seal, in accordance with the requirements of Item 1, page 15, above. Permanent conductor casing may be used if it is installed in accordance with Item 3, below and Item 5 (page 32 of Bulletin 74-81) and it extends to at least the depth specified in Subsection A, above.

3. Wells drilled in soft consolidated formations (extensive clays, sandstones, etc.). An 'oversized' hole, at least 4 inches greater in diameter than the outside diameter of the well casing, shall be drilled to at least the depth specified in Subsection A, page 14, above. The space between the well casing and the borehole shall be filled with sealing material to at least the depth specified in Subsection A, above, as shown by Figure 4C (page 31 of Bulletin 74-81).

If a permanent conductor casing is to be installed to facilitate the construction of the well, an oversized hole, at least 4 inches greater in diameter than the outside surface of the permanent conductor casing, shall be drilled to the bottom of the conductor casing or to at least the depth specified in Subsection A, above, and the annular space between the conductor casing and the borehole wall filled with sealing material. In some cases, such as in cable tool drilling, it may be necessary to extend permanent conductor casing beyond the depth of the required depth of the annular surface seal in order to maintain the borehole. Sealing material is not required between conductor



casing and the borehole wall other than the depths specified in Subsection A, above, and Section 13, below (page 46 of Bulletin 74-81)."

Items 4 through 7 (page 32 of Bulletin 74-81) are unchanged. Item 8 has been added, as follows:

- "8. Wells that penetrate zones containing poor-quality water, pollutants, or contaminants. If geologic units or fill known or suspected to contain poor-quality water, pollutants, or contaminants are penetrated during drilling, and, the possibility exists that poor-quality water, pollutants, or contaminants could move through the borehole during drilling and well construction operations and significantly degrade ground water quality in other units before sealing material can be installed, then precautions shall be taken to seal off or 'isolate' zones containing poor-quality water, pollutants, and contaminants during drilling and well construction operations. Special precautions could include the use of temporary or permanent conductor casing, borehole liners, and specialized drilling equipment. The use of conductor casing is described in Item 1, page 15, above."

Subsection C (page 34 of Bulletin 74-81) is unchanged. Subsections D, E, and F (page 34 of Bulletin 74-81) have been changed to read as follows:

- "D. Sealing Material. Sealing material shall consist of neat cement, sand cement, concrete, or bentonite. Cuttings from drilling, or drilling mud, shall not be used for any part of the sealing material.
1. Water. Water used to prepare sealing mixtures should generally be of drinking water quality, shall be compatible with the type of sealing material used, be free of petroleum and petroleum products, and be free of suspended matter. In some cases water considered nonpotable, with a maximum of 2,000 milligrams per liter chloride and 1,500 mg/l sulfate, can be used for cement-based sealing mixtures. The quality of water to be used for sealing mixtures shall be determined where unknown.
  2. Cement. Cement used in sealing mixtures shall meet the requirements of American Society for Testing and Materials C150, *Standard Specification for Portland Cement*, including the latest revisions thereof.

Types of Portland cement available under ASTM C150 for general construction are:

- Type I - General purpose. Similar to American Petroleum Institute Class A.
- Type II - Moderate resistance to sulfate. Lower heat of hydration than Type I. Similar to API Class B.
- Type III - High early strength. Reduced curing time but higher heat of hydration than Type I. Similar to API Class C.
- Type IV - Extended setting time. Lower heat of hydration than Types I and III.
- Type V - High sulfate resistance.

Special cement setting accelerators and retardants and other additives may be used in some cases. Special field additives for Portland cement mixtures shall meet the requirements of ASTM C494, *Standard Specification for Chemical Admixtures for Concrete*, and latest revision thereof.



Hydrated lime may be added up to 10 percent of the volume of cement used to make the seal mix more fluid. Bentonite may be added to cement-based mixes, up to 6 percent by weight of cement used, to improve fluid characteristics of the sealing mix and reduce the rate of heat generation during setting.

Dry additives should be mixed with dry cement before adding water to the mixture to ensure proper mixing, uniformity of hydration, and an effective and homogeneous seal. The water demand of additives shall be taken into account when water is added to the mix.

Minimum times required for sealing materials containing Portland cement to set and begin curing before construction operations on a well can be resumed are:

- Types I and II cement - 24 hours
- Type III cement - 12 hours
- Type V cement - 6 hours

Type IV cement is seldom used for annular seals because of its extended setting time.

Allowable setting times may be reduced or lengthened by use of accelerators or retardants specifically designed to modify setting time, at the approval of the enforcing agency.

More time shall be required for cement-based seals to cure to allow greater strength when construction or development operations following the placement of the seal may subject casing and sealing materials to significant stress. Subjecting a well to significant stress before a cement-based sealing material has adequately cured can damage the seal and prevent proper bonding of cement-based sealants to casing(s).

If plastic well casing is used, care shall be exercised to control the heat of hydration generated during the setting and curing of cement in an annular seal. Heat can cause plastic casing to weaken and collapse. Heat generation is a special concern if thin-wall plastic well casing is used, if the well casing will be subject to significant net external pressure before the setting of the seal, and/or if the radial thickness of the annular seal is large. Additives that accelerate cement setting also tend to increase the rate of heat generation during setting and, thus, should be used with caution where plastic casing is employed.

The temperature of a setting cement seal can be lowered by circulating water inside the well casing and/or by adding bentonite to the cement mixture, up to 6 percent by weight of cement used.

Cement-based sealing material shall be constituted as follows:

- a. Neat Cement. For Types I or II Portland cement, neat cement shall be mixed at a ratio of one 94-pound sack of Portland cement to 5 to 6 gallons of 'clean' water. Additional water may be required where special additives, such as bentonite, or 'accelerators' or 'retardants' are used.
- b. Sand Cement. Sand-cement shall be mixed at a ratio of not more than 188 pounds of sand to one 94-pound sack of Portland cement (2 parts sand to 1 part cement, by weight) and about 7 gallons of clean water, where Type I or Type II Portland cement is used. This is equivalent to a '10.3 sack mix.' Less

water shall be used if less sand than 2 parts sand per one part cement by weight is used. Additional water may be required when special additives, such as bentonite, or 'accelerators' or 'retardants' are used.

- c. Concrete. Concrete is often useful for large volume annular seals, such as in large-diameter wells. The proper use of aggregate can decrease the permeability of the annular seal, reduce shrinkage, and reduce the heat of hydration generated by the seal.

Concrete shall consist of Portland cement and aggregate mixed at a ratio of at least six-94 pound sacks of Portland cement per cubic yard of aggregate. A popular concrete mix consists of eight-94 pound sacks of Type I or Type II Portland cement per cubic yard of uniform 3/8-inch aggregate.

In no case shall the size of the aggregate be more than 1/5 the radial thickness of the annular seal. Water shall be added to concrete mixes to attain proper consistency for placement, setting, and curing.

- d. Mixing. Cement-based sealing materials shall be mixed thoroughly to provide uniformity and ensure that no 'lumps' exist.

Ratios of the components of cement-based sealing materials can be varied depending on the type of cement and additives used. Variations must be approved by the enforcing agency.

- 3. Bentonite. Bentonite clay in 'gel' form has some of the advantages of cement-based sealing material. A disadvantage is that the clay can sometimes separate from the clay-water mixture.

Although many types of clay mixtures are available, none has sealing properties comparable to bentonite clay. Bentonite expands significantly in volume when hydrated. Only bentonite clay is an acceptable clay for annular seals.

Unamended bentonite clay seals should not be used where structural strength of the seal is required, or where it will dry. Bentonite seals may have a tendency to dry, shrink and crack in arid and semi-arid areas of California where subsurface moisture levels can be low. Bentonite clay seals can be adversely affected by subsurface chemical conditions, as can cement-based materials.

Bentonite clay shall not be used as a sealing material if roots from trees and other deep rooted plants might invade and disrupt the seal, and/or damage the well casing. Roots may grow in an interval containing a bentonite seal depending on surrounding soil conditions and vegetation.

Bentonite-based sealing material shall not be used for sealing intervals of fractured rock or sealing intervals of highly unstable, unconsolidated material that could collapse and displace the sealing material, unless otherwise approved by the enforcing agency. Bentonite clay shall not be used as a sealing material where flowing water might erode it.

Bentonite clay products used for sealing material must be specifically prepared for such use. Used drilling mud and/or cuttings from drilling shall not be used in sealing material.

Bentonite used for annular seals shall be commercially prepared, powdered, granulated, pelletized, or chipped/crushed sodium montmorillonite clay. The largest dimension of pellets or chips shall be less than 1/5 the radial thickness of the annular space into which they are placed.

Bentonite clay mixtures shall be thoroughly mixed with clean water *prior to placement*. A sufficient amount of water shall be added to bentonite to allow proper hydration. Depending on the bentonite sealing mixture used, 1 gallon of water should be added to about every 2 pounds of bentonite. Water added to bentonite for hydration shall be of suitable quality and free of pollutants and contaminants.

Bentonite preparations normally require 1/2 to 1 hour to adequately hydrate. Actual hydration time is a function of site conditions and the form of bentonite used. Finely divided forms of bentonite generally require less time for hydration, if properly mixed.

Dry bentonite pellets or chips may be placed directly into the annular space below water, where a short section of annular space, up to 10 feet in length, is to be sealed. Care shall be taken to prevent bridging during the placement of bentonite seal material.

- E. Radial Thickness of Seal. A minimum of two inches of sealing material shall be maintained between all casings and the borehole wall, within the interval to be sealed, except where temporary conductor casing cannot be removed, as noted in Subsection B, page 15, above. A minimum of two inches of sealing material shall also be maintained between each casing, such as permanent conductor casing, well casing, gravel fill pipes, etc., in a borehole within the interval to be sealed, unless otherwise approved by the enforcing agency. Additional space shall be provided, where needed, for casings to be properly centralized and spaced and allow the use of a tremie pipe during well construction (if required), especially for deeper wells.

F. Placement of Seal.

1. Obstructions. All loose cuttings, or other obstructions to sealing shall be removed from the annular space before placement of the annular seal.
2. Centralizers. Well casing shall be equipped with centering guides or 'centralizers' to ensure the 2-inch minimum radial thickness of the annular seal is at least maintained. Centralizers need not be used in cases where the well casing is centered in the borehole during well construction by use of removable tools, such as hollow-stem augers.

The spacing of centralizers is normally dictated by the casing materials used, the orientation and straightness of the borehole, and the method used to install the casing.

Centralizers shall be metal, plastic, or other non-degradable material. Wood shall not be used as a centralizer material. Centralizers must be positioned to allow the proper placement of sealing material around casing within the interval to be sealed.

Any metallic component of a centralizer used with metallic casing shall consist of the same material as the casing. Metallic centralizer components shall meet the same metallurgical specifications and standards as the metallic casing to reduce the potential for galvanic corrosion of the casing.



3. Foundation and Transition Seals. A packer or similar retaining device, or a small quantity of sealant that is allowed to set, can be placed at the bottom of the interval to be sealed before final sealing operations begin to form a foundation for the seal.

A transition seal, up to 5 feet in length, consisting of bentonite, is sometimes placed in the annular space to separate filter pack and cement-based sealing materials. The transition seal can prevent cement-based sealing materials from infiltrating the filter pack. A short interval of fine-grained sand, usually less than 2 feet in length, is sometimes placed between the filter pack and the bentonite transition seal to prevent bentonite from entering the filter pack. Also, fine sand is sometimes used in place of bentonite as the transition seal material.

Fine-sized forms of bentonite, such as granules and powder, are usually employed for transition seals if a transition seal is to be placed above the water level in a well boring. Coarse forms of bentonite, such as pellets and chips, are often used where a bentonite transition seal is to be placed below the water level.

Transition seals should be installed by use of a tremie pipe, or equivalent. However, some forms of bentonite may tend to bridge or clog in a tremie pipe.

Bentonite can be placed in dry form or as slurry for use in transition seals. Water should be added to the bentonite transition seal prior to the placement of cement-based sealing materials where bentonite is dry in the borehole. Care should be exercised during the addition of water to the borehole to prevent displacing the bentonite.

Water should be added to bentonite at a ratio of about 1 gallon for every 2 pounds of bentonite to allow for proper hydration. Water added to bentonite for hydration shall be of suitable quality and free of pollutants and contaminants.

Sufficient time should be allowed for bentonite transition seals to properly hydrate before cement-based sealing materials are placed. Normally, 1/2 to 1 hour is required for proper hydration to occur. Actual time of hydration is a function of site conditions.

The top of the transition seal shall be sounded to ensure that no bridging has occurred during placement.

4. Timing and Method of Placement. The annular space shall be sealed as soon as practical after completion of drilling or a stage of drilling. In no case shall the annular space be left unsealed longer than 14 days following the installation of casing.

Sealing material shall be placed in one continuous operation from the bottom of the interval to be sealed, to the top of the interval. Where the seal is more than 100 feet in length, the deepest portion of the seal may be installed first and allowed to set or partially set. The deep initial seal shall be no longer than 10 feet in length. The remainder of the seal shall be placed above the initial segment in one continuous operation.

Sealing material shall be placed by methods (such as the use of a tremie pipe or equivalent) that prevent freefall, bridging, or dilution of the sealing material, or separation of sand or aggregate from the sealing material. Annular sealing materials

shall not be installed by freefall unless the interval to be sealed is dry and no deeper than 30 feet below ground surface.

5. Ground Water Flow. Special care shall be used to restrict the flow of ground water into a well boring while placing material, where subsurface pressure causing the flow of water is significant.
6. Verification. It shall be verified that the volume of sealing material placed at least equals or exceeds the volume to be sealed.
7. Pressure. Pressure required for placement of sealing materials shall be maintained long enough for cement-based sealing materials to properly set."

#### Section 10. Surface Construction Features.

Subsection A, Item 5; Subsection B; and Subsection F (page 39 of Bulletin 74-81) have been changed. The remainder of Section 10 (page 36 of Bulletin 74-81) is unchanged.

##### "A. Openings.

5. Bases. A concrete base or pad, sometimes called a pump block or pump pedestal, shall be constructed at ground surface around the top of the well casing and contact the annular seal, unless the top of the casing is below ground surface, as provided by Subsection B, page 23, below.

The base shall be free of cracks, voids, or other significant defects likely to prevent water tightness. Contacts between the base and the annular seal, and the base and the well casing, must be water tight and must not cause the failure of the annular seal or well casing. Where cement-based annular sealing material is used, the concrete base shall be poured before the annular seal has set, unless otherwise approved by the enforcing agency.

The upper surface of the base shall slope away from the well casing. The base shall extend at least two feet laterally in all directions from the outside of the well boring, unless otherwise approved by the enforcing agency. The base shall be a minimum of 4 inches thick.

A minimum base thickness of 4 inches is normally acceptable for small diameter, single-user domestic wells. The base thickness should be increased for larger wells. Shape and design requirements for well pump bases vary with the size, weight, and type of pumping equipment to be installed, engineering properties of the soil on which the base is to be placed, and local environmental conditions. A large variety of base designs have been used. The Vertical Turbine Pump Association has developed a standard base design for large lineshaft turbine pumps. This design consists of a square, concrete pump base whose design is dependent on bearing weight and site soil characteristics.

Where freezing conditions require the use of a pitless adapter, and the well casing and annular seal do not extend above ground surface or into a pit or vault, a concrete base or pad shall be constructed as a permanent location monument for the covered well. The base shall be 3 feet in length on each side and 4 inches in thickness, unless

otherwise approved by the enforcing agency. The base shall have a lift-out section, or equivalent, to allow access to the well. The lift-out shall facilitate inspection and repair of the well.

- B. Well Pits or Vaults. The use of well pits, vaults, or equivalent features to house the top of a well casing below ground surface shall be avoided, if possible, because of their susceptibility to the entrance of poor-quality water, contaminants and pollutants. Well pits or vaults can only be used if approval is obtained from the enforcing agency. A substitute device, such as a pitless adapter or pitless adapter unit (a variation), should almost always be used in place of a vault or pit.

Pitless adapters and units were developed for use in areas where prolonged freezing occurs, and below ground (frost line) discharges are common. Both the National Sanitation Foundation and Water Systems Council have developed standards for the manufacture and installation of pitless adapters and units. (See Appendix E, Bibliography, page 85 of Bulletin 74-81.)

If a pit or vault is used it shall be watertight and structurally sound. The vault shall extend from the top of the annular seal to at least ground surface.

The vault shall contact the annular seal in a manner to form a watertight and structurally sound connection. Contacts between the vault and the annular seal, and the vault and the well casing, if any, shall not fail or cause the failure of the well casing or annular seal.

Where cement-based annular seal materials are used, the vault shall be set into or contact the annular seal material before it sets, unless otherwise approved by the enforcing agency. If bentonite-based sealing material is used for the annular seal, the vault should be set into the bentonite before it is fully hydrated.

Cement-based sealing material shall be placed between the outer walls of the vault and the excavation into which it is placed to form a proper, structurally sound foundation for the vault, and to seal the space between the vault and excavation.

The sealing material surrounding a vault shall extend from the top of the annular seal to ground surface unless precluded in areas of freezing. If cement-based sealing material is used for both the annular seal and the space between the excavation and vault, the sealing material shall be emplaced in a 'continuous pour'. In other words, cement-based sealing material shall be placed between the vault and excavation and contact the cement-based annular seal before the annular seal has set.

The vault cover or lid shall be watertight but shall allow the venting of gases. The lid shall be fitted with a security device to prevent unauthorized access. The outside of the lid shall be clearly and permanently labeled 'WATER WELL'. The vault and its lid shall be strong enough to support vehicular traffic where such traffic might occur.

The top of the vault shall be set at, or above, grade so that drainage is away from the vault. The top of the well casing contained within the vault shall be covered in accordance with requirements under Subsection A, above, (page 36, Bulletin 74-81) so that water, contaminants, and pollutants that may enter the vault will not enter the well casing. The cover shall be provided with a pressure relief or venting device for gases.



- F. Backflow Prevention. All pump discharge pipes not discharging or open to the atmosphere shall be equipped with an automatic device to prevent backflow and/or back siphonage into a well. Specific backflow prevention measures are required for drinking water supply wells, as prescribed in Title 17, Public Health, California Code of Regulations (Sections 7583-7585 and 7601-7605, effective June 25, 1987).

Irrigation well systems, including those used for landscape irrigation, and other well systems that employ, or which have been modified to employ, chemical feeders or injectors shall be equipped with a backflow prevention device(s) approved by the enforcing agency."

## Section 12. Casing.

Items 3, 5, and 6 of Subsection A (page 43 of Bulletin 74-81) have been revised. The remainder of Subsection A is unchanged. Subsection B (page 45 of Bulletin 74-81) has been revised. The revisions are as follows:

### "A. Casing Material.

3. Plastic. Two basic types of plastic are commonly used for plastic well casing: thermoplastics and thermosets. Thermoplastics soften with the application of heat and reharden when cooled. Thermoplastics can be reformed repeatedly using heat and sometimes can unexpectedly deform. Attention should be given to the effect of heat on thermoplastic casing from the setting and curing of cement. Additional discussion on sealing material and heat generation is in Section 9, Subsection D, 'Sealing Material'.

Thermoplastics used for well casing include ABS (acrylonitrile butadiene styrene), PVC (polyvinyl chloride), and SR (styrene rubber). PVC is the most frequently used thermoplastic well casing in California. Styrene rubber is seldom used.

Unlike thermoplastics, thermoset plastics cannot be reformed after heating. The molecules of thermoset plastic are 'set' during manufacturing by heat, chemical action, or a combination of both. The thermoset plastic most commonly used for well casing is fiberglass.

- a. Thermoplastics. Thermoplastic well casing shall meet the requirements of ASTM F480, *Standard Specification for Thermoplastic Well Casing Pipe and Couplings Made in Standard Dimension Ratios (SDR), SCH 40 and SCH 80*, including the latest revision thereof. (Note: A 'dimension ratio' is the ratio of pipe diameter to pipe wall thickness.)

Pipe made in Schedule 40 and 80 wall thicknesses and pipe designated according to certain pressure classifications are listed in ASTM F480, as well as casing specials referencing the following ASTM specifications:

- (1) ABS Pipe. ASTM D1527, *Standard Specification for Acrylonitrile-Butadiene-Styrene (ABS) Plastic Pipe, Schedules 40 and 80.*
- (2) PVC Pipe. ASTM D1785, *Standard Specification for (Poly Vinyl Chloride) (PVC) Plastic Pipe, Schedules 40, 80, and 120.*
- (3) Pressure-Rated PVC Pipe. ASTM D2241, *Standard Specifications for Poly (Vinyl Chloride) (PVC) Pressure-Rated Pipe (SDR Series).*

Thermoplastic well casing that may be subject to significant impact stress during or after installation shall meet or exceed the requirements for impact resistance classification set forth in Section 6.5 of ASTM F480. Casing that may be subject to significant impact forces includes, but is not limited to; casing that is installed in large diameter, deep boreholes; and casing through which drilling tools pass following installation of the casing in a borehole.

- b. Thermoset Plastics. Thermoset casing material shall meet the following specifications, as applicable, including the latest revisions thereof:
    - (1) Filament Wound Resin Pipe. ASTM D2996, *Standard Specification for Filament Wound Reinforced Thermosetting Resin Pipe.*
    - (2) Centrifugally Cast Resin Pipe. ASTM D2997, *Standard Specification for Centrifugally Cast Reinforced Thermosetting Resin Pipe.*
    - (3) Reinforced Plastic Mortar Pressure Pipe. ASTM D3517, *Standard Specification for Reinforced Plastic Mortar Pressure Pipe.*
    - (4) Glass Fiber Reinforced Resin Pressure Pipe. AWWA<sup>1</sup> C950, *AWWA Standard for Glass-Fiber-Reinforced Thermosetting-Resin Pressure Pipe.*
  - c. Drinking Water Supply. All plastic casing used for drinking water supply wells, including community supply well and individual domestic wells, shall meet the provisions of National Sanitation Foundation Standard No. 14, *Plastic Piping Components and Related Materials* and any revision thereof. The casing shall be marked or labeled following requirements in NSF Standard No. 14. Standard No. 14 includes the requirements of ASTM F480.
  - d. Storage, Handling, and Transportation. Plastic casing shall not be stored in direct sunlight or subjected to freezing temperatures for extended periods of time. Plastic casing shall be stored, handled, and transported in a manner that prevents excessive mechanical stress. Casing shall be protected from sagging and bending, severe impacts and loads, and potentially harmful chemicals.
  - e. Large Diameter Wells. Because large diameter plastic casing has not been used extensively at depths exceeding 500 feet, special care shall be exercised with its use in deep wells.
5. Unacceptable Casing Materials. Galvanized sheet metal pipe such as 'downspout,' tile pipe, or natural wood shall not be used as well casing.
  6. Other Materials. Materials in addition to those described above may be used as well casing, subject to enforcing agency approval."

Subsection B (page 45 of Bulletin 74-81) has been revised as follows:

- "B. Casing Installation. All well casing shall be assembled and installed with sufficient care to prevent damage to casing sections and joints. All casing joints above intervals of perforations

<sup>1</sup> American Water Works Association.



or screen shall be watertight. Any perforations shall be below the depths specified in Section 9, Subsection A, page 14, above.

Casing shall be equipped with centering guides or 'centralizers' to ensure the even radial thickness of the annular seal and filter pack.

1. Metallic Casing. Metallic casing may be joined by welds, threads, or threaded couplings. Welding shall be accomplished in accordance with the standards of the American Welding Society or the most recent revision of the American Society of Mechanical Engineers Boiler Construction Code. Metallic casing shall be equipped with a 'drive shoe' at the lower end if it is driven into place.
2. Plastic Casing. Plastic casing may be joined by solvent welding or mechanically joined by threads or other means, depending on the type of material and its fabrication. Solvent cement used for solvent welding shall meet specifications for the type of plastic casing used. Solvent cement shall be applied in accordance with solvent and casing manufacturer instructions. Particular attention shall be given to instructions pertaining to required setting time for joints to develop strength.

The following specifications for solvent cements and joints for PVC casing shall be met, including the latest revisions thereof:

- a. ASTM D2564, *Standard Specification for Solvent Cements for Poly (Vinyl Chloride) (PVC) Plastic Pipe and Fittings.*
- b. ASTM D2855, *Standard Practice for Making Solvent-Cemented Joints with Poly (Vinyl Chloride) (PVC) Pipe and Fittings.*

Plastic casing or screen shall not be subjected to excessive stress during installation and shall not be driven into place. Care shall be taken to ensure that plastic casing and joints are not subjected to excessive heat from cement-based sealing material.

A specifically designed adapter shall be used to join plastic casing to metallic casing or screen."

#### Section 14. Well Development.

Section 14 (page 46 of Bulletin 74-81) has been revised as follows:

"Development, redevelopment, or reconditioning of a well shall be performed with care, by methods that will not damage the well structure or destroy natural barriers to the movement of poor quality water, pollutants, and contaminants.

Acceptable well development, redevelopment, or reconditioning methods include:

- Overpumping;
- Surging or swabbing by use of 'plungers';
- Surging with compressed air;
- Backwashing or surging by alternately starting and stopping a pump;
- Jetting with water;

- Introducing specifically-formulated chemicals into a well; and,
- Combinations of the above.

Hydraulic fracturing (hydrofracturing) is sometimes an acceptable well development and redevelopment method when properly performed. Good quality water shall be used in hydrofracturing. The water shall be disinfected prior to introduction into a well. Material used as 'propping' agents shall be free of pollutants and contaminants, shall be compatible with the use of a well, and shall be thoroughly washed and disinfected prior to placement in a well.

Development, redevelopment, or reconditioning by use of specially designed **explosive charges** is in some cases, another acceptable development method. Explosives shall be used with special care to prevent damage to the well structure and to any natural barriers to the movement of poor-quality water, pollutants, and contaminants. Explosives shall only be used by properly-trained personnel.

Wells subjected to chemicals or explosives during development, redevelopment, or reconditioning operations shall be thoroughly pumped to remove such agents and residues immediately after the completion of operations. Chemicals, water, and other wastes removed from the well shall be disposed of in accordance with applicable local, State, and federal requirements. The enforcing agency should be contacted regarding the proper disposal of waste."

## Part III. Destruction of Wells

### Section 21. Definition of "Abandoned" Well.

Section 21 (page 52 of Bulletin 74-81) has been revised as follows:

"A well is considered 'abandoned' or permanently inactive if it has not been used for one year, unless the owner demonstrates intention to use the well again. In accordance with Section 24400 of the California Health and Safety Code, the well owner shall properly maintain an inactive well as evidence of intention for future use in such a way that the following requirements are met:

- "(1) The well shall not allow impairment of the quality of water within the well and ground water encountered by the well.
- (2) The top of the well or well casing shall be provided with a cover, that is secured by a lock or by other means to prevent its removal without the use of equipment or tools, to prevent unauthorized access, to prevent a safety hazard to humans and animals, and to prevent illegal disposal of wastes in the well. The cover shall be watertight where the top of the well casing or other surface openings to the well are below ground level, such as in a vault or below known levels of flooding. The cover shall be watertight if the well is inactive for more than five consecutive years. A pump motor, angle drive, or other surface feature of a well, when in compliance with the above provisions, shall suffice as a cover.
- (3) The well shall be marked so as to be easily visible and located, and labeled so as to be easily identified as a well.
- (4) The area surrounding the well shall be kept clear of brush, debris, and waste materials."

If a pump has been temporarily removed for repair or replacement, the well shall not be considered 'abandoned' if the above conditions are met. The well shall be adequately covered to prevent injury to people and animals and to prevent the entrance of foreign material, surface water, pollutants, or contaminants into the well during the pump repair period."

### Section 23. Requirements for Destroying Wells.

Subsection A, Item 1 (page 53 of Bulletin 74-81) and Subsection B, Item 1, (page 54, of Bulletin 74-81) have been changed. The remainder of Section 23 is unchanged.

Subsection A, Item 1 has been revised as follows:

- "1. Obstructions. The well shall be cleaned, as needed, so that all undesirable materials, including obstructions to filling and sealing, debris, oil from oil-lubricated pumps, or pollutants and contaminants that could interfere with well destruction are removed for disposal.

The enforcing agency shall be notified as soon as possible if pollutants and contaminants are known or suspected to be in a well to be destroyed. Well destruction operations may then proceed only at the approval of the enforcing agency.

The enforcing agency should be contacted to determine requirements for proper disposal of materials removed from a well to be destroyed."

Subsection B, Item 1 has been revised as follows:

- "1. Wells situated in unconsolidated material in an unconfined ground water zone. In all cases the upper 20 feet of the well shall be sealed with suitable sealing material and the remainder of the well shall be filled with suitable fill, or sealing material. (See Figure 9A, page 55 of Bulletin 74-81.)"

# MONITORING WELLS



# MONITORING WELL STANDARDS

## INTRODUCTION

Ground water monitoring wells are principally used for observing ground water levels and flow conditions, obtaining samples for determining ground water quality, and for evaluating hydraulic properties of water-bearing strata. Monitoring wells are sometimes referred to as "observation wells."

The quality of water intercepted by a monitoring well can range from drinking water to highly polluted water. In contrast, production or "water wells" are usually designed to obtain water from productive zones containing good-quality water.

The screen or perforated section of a monitoring well usually extends only a short length to obtain water from, or to monitor conditions within, an individual water-bearing unit or zone. Water wells are often designed to obtain water from multiple water-bearing strata. Although there are usually differences between the design and function of monitoring wells and water wells, water wells sometimes are used as monitoring wells, and vice versa.

Monitoring wells, along with other types of wells, can provide a pathway for the movement of poor-quality water, pollutants, and contaminants. Because monitoring wells are often purposely located in areas affected by pollutants and contaminants, they pose an especially significant threat to ground water quality if they are not properly constructed, altered, maintained, and destroyed.

The California Legislature amended the California Water Code in 1986 specifically to include requirements for monitoring well standards. Monitoring wells were previously assumed by the Department to be covered by the collective term "well" in the law.

## History of Monitoring Wells

Monitoring wells were first used mainly for water level measurement. These wells were often referred to as piezometers in reference to the "piezometric surface" of ground water. In recent years, the term "piezometric surface" is often replaced by "potentiometric surface." However, the term "piezometer" is still sometimes used for monitoring wells installed only for water level measurement.

Many water level monitoring wells constructed in the past were relatively large in diameter in comparison to today's monitoring wells. Wells up to 10-inches in diameter were often constructed to accommodate various means of water level measurement, including floats for mechanically-operated, continuous water level recorders. Many inactive water wells that could accommodate mechanical water level recording equipment were used as monitoring wells.

Modern electronic water level measuring and recording devices now allow for small-diameter water-level monitoring wells. Some continuous water-level measurement devices can be used in wells less than 2-inches in inside diameter.

The use of monitoring wells for ground water sampling for chemical analysis has increased significantly in the past two decades. The following factors have all served to increase the frequency and scope of ground water quality investigations and the number of monitoring wells constructed:

- Advances in analytical and environmental chemistry;
- Increased knowledge of the adverse effects of chemicals on humans;
- Public awareness of ground water pollution;
- The advent of federal ground water quality protection legislation in the 1970s, and,
- Statutes relating to ground water quality enacted by the California Legislature.

Since the 1970s an entire industry has developed around ground water quality monitoring and monitoring well construction. Numerous private firms are involved in providing technical services for the design and implementation of ground water quality investigations. Many firms are involved in the manufacture, distribution, and marketing of materials and equipment used in constructing and operating monitoring wells.

Most monitoring wells constructed today are used to assess:

- The nature and distribution of pollutants and contaminants in ground water;
- The nature and distribution of naturally occurring chemical constituents;
- Subsurface hydrologic conditions; and,
- Hydraulic properties of strata as they relate to pollutant and contaminant movement.

Some monitoring wells are designed to be multipurpose. Monitoring wells can sometimes be used as "extraction" or "injection" wells for mitigation of pollution or contamination.

Although a significant number of monitoring wells constructed today are for detection and assessment of ground water quality impairment, many monitoring wells are constructed for evaluating ground water supply conditions by allowing ground water level measurement and/or aquifer testing. Still others are constructed for observing water levels associated with excavations and irrigated agriculture.

During 1989, approximately 20 percent of all well drilling in California was for monitoring wells, based on well driller's reports received by the Department of Water Resources. Monitoring wells have been constructed in nearly all California counties. The largest concentrations of water quality monitoring wells occur in metropolitan areas of the State. Large numbers of monitoring wells are installed for detection and assessment of leaks from underground storage tanks.

## Types of Monitoring Wells

For the purpose of these standards, the term "monitoring well" is limited to wells designed to monitor subsurface water in the saturated zone, existing at or above atmospheric pressure (ground water); rather than water, water vapor, and/or gases contained in the unsaturated or vadose zone. Monitoring devices used for the unsaturated zone differ significantly from those used for the saturated (ground water) zone.

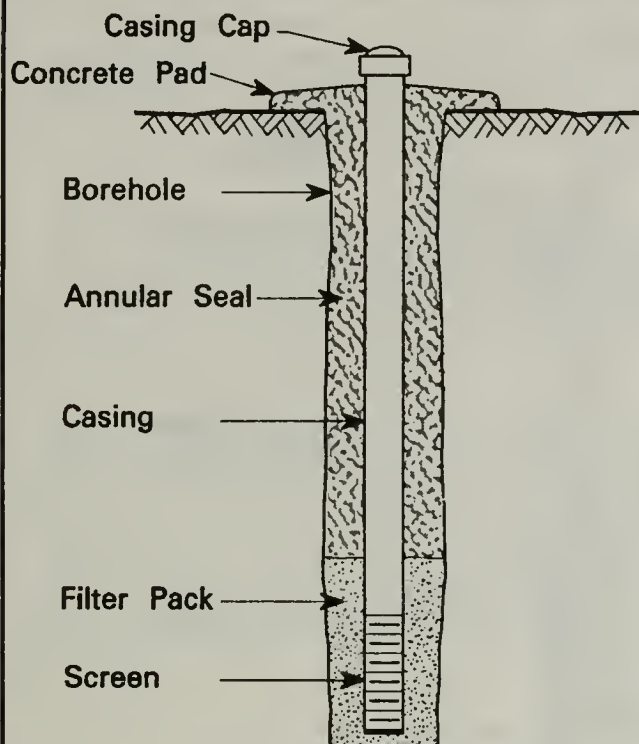
As shown in Figure 2, three basic types of monitoring wells or "installations" are:

- Individual monitoring wells;
- Nested monitoring wells; and,
- Clustered monitoring wells.

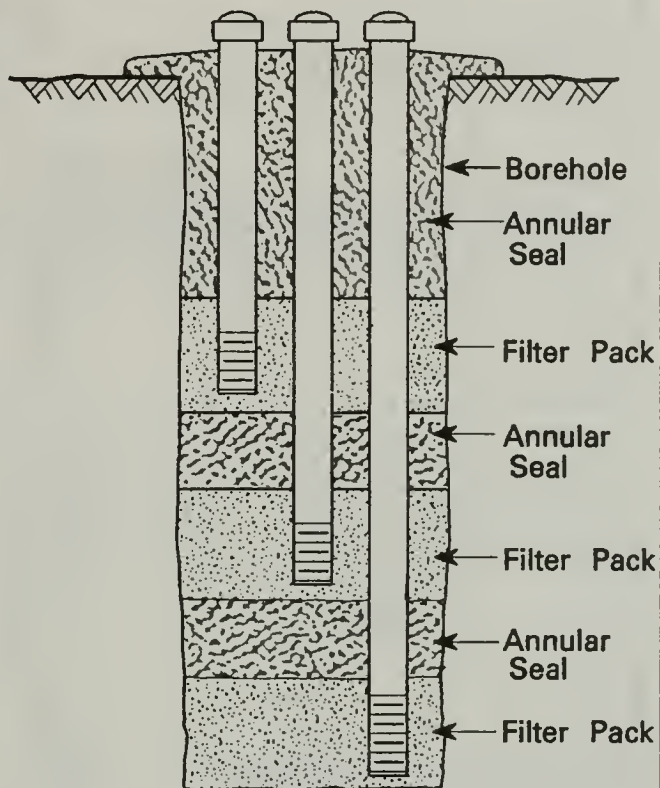
Individual monitoring wells consist of a single casing "string" within a borehole, as illustrated in Figures 2 and 3. Individual monitoring wells are installed in unique locations apart from one another. They are the most common type of monitoring well constructed in California.

# Figure 2. MONITORING WELL TYPES

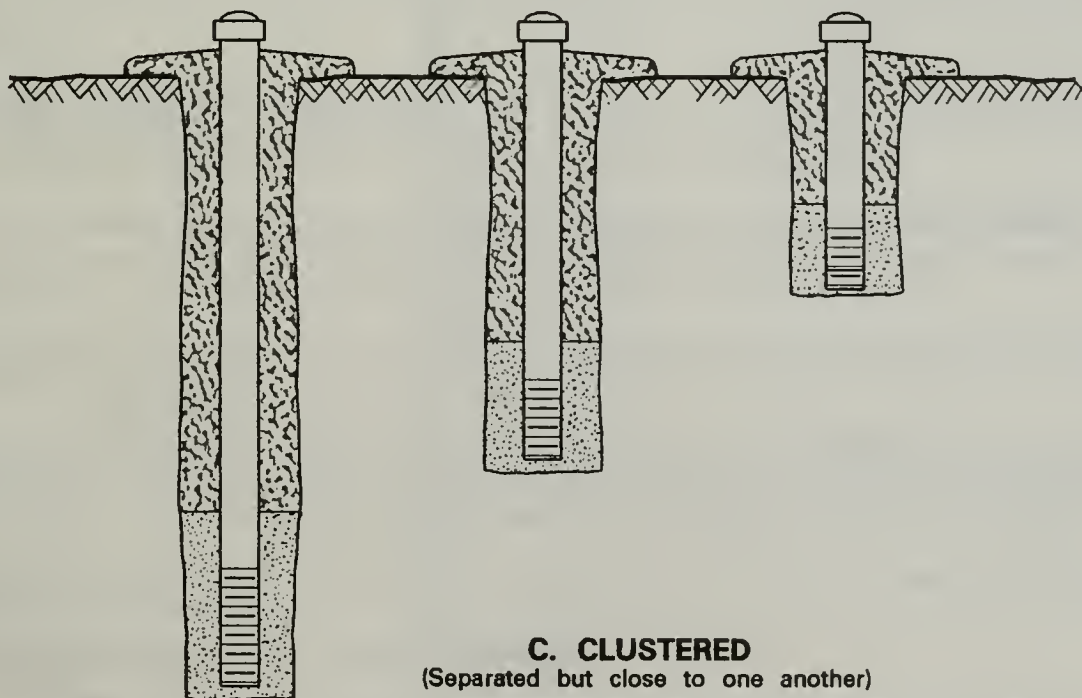
(NOTE: Schematic, not to scale)



**A. INDIVIDUAL**



**B. NESTED**



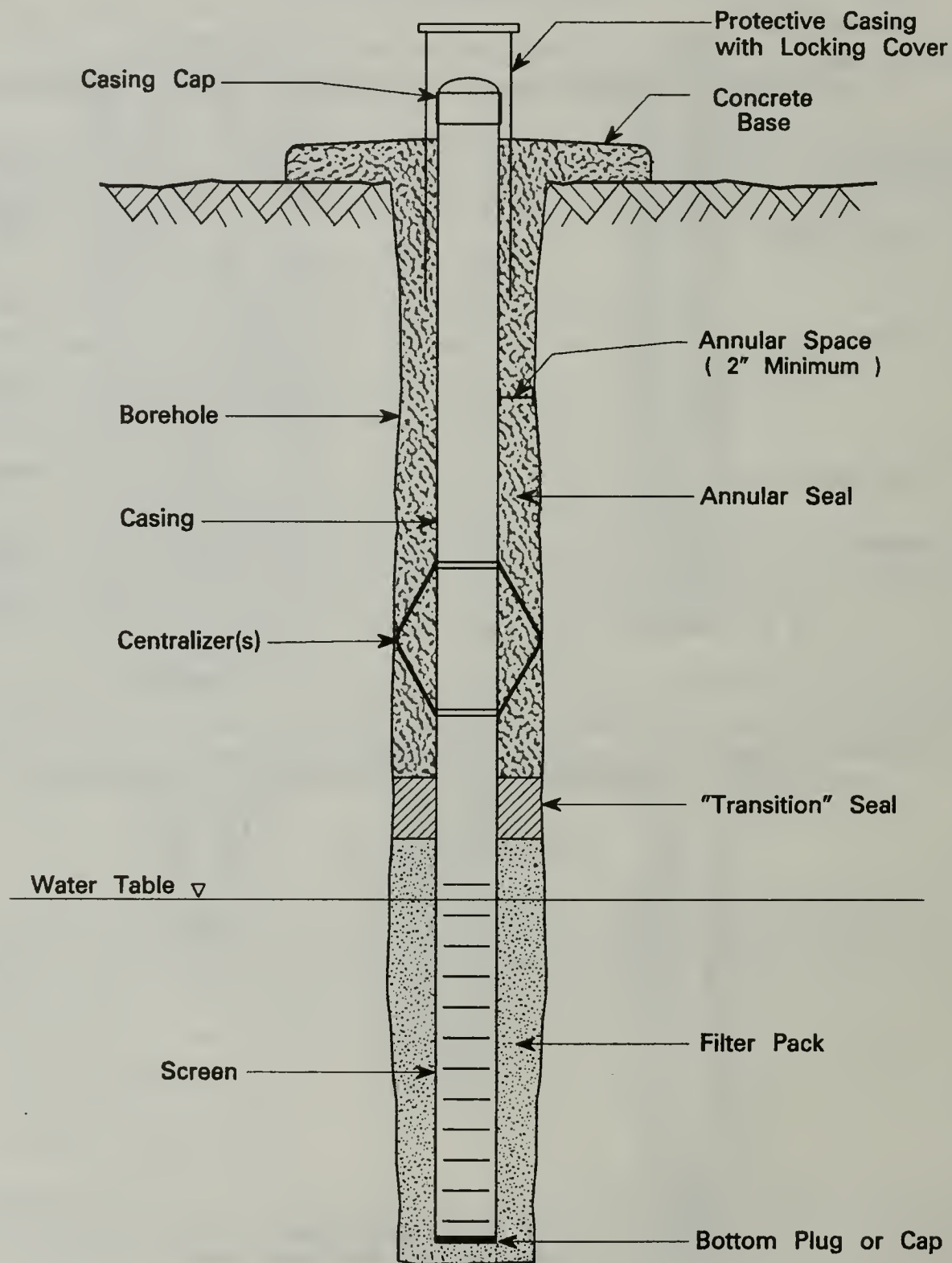
**C. CLUSTERED**

(Separated but close to one another)



**Figure 3. CROSS SECTION OF A TYPICAL MONITORING WELL**

(NOTE: Schematic, not to scale)



**Nested monitoring wells** consist of two or more casing strings within the same borehole. Normally the screened interval of each casing string is designed to obtain water from different aquifers or water-bearing zones. The purpose of a nested monitoring well is much the same as clustered monitoring wells.

**Clustered monitoring wells** consist of individual monitoring wells situated close together, but not in the same borehole. The wells within a cluster are normally constructed to obtain water from different aquifers or water-bearing zones. Clustered wells are most often used for monitoring ground water conditions at various depths in roughly the same area.

A nested monitoring well can be difficult to construct because of multiple casings within the same borehole. Care is required during construction to ensure water-bearing zones for each casing string are hydraulically isolated from one another and the annular seals are effective. Some regulatory agencies may prohibit the use of nested monitoring wells for certain contamination or pollution investigations. Normally this can be due to uncertainties about whether water-bearing strata can be isolated and whether the annular seals in a nested well are always effective.

Individual casing strings for the various types of monitoring wells discussed above, are sometimes designed to obtain water from more than one aquifer or water-bearing unit. These casing strings usually have multiple intervals of openings or screen. Such well casing strings, often referred to as "multi-level monitoring wells," can sometimes serve as a preferential pathway for the movement of poor quality water, pollutants, and contaminants from one unit to another. Some regulatory agencies prohibit the use of multi-level monitoring wells for certain pollution or contamination investigations out of concern for water quality protection and data quality requirements.

### Authority and Responsibilities of Other Agencies

As discussed above, Congress enacted major legislation dealing with ground water quality protection during the 1970s. Regulatory programs initiated by federal legislation, such as the Resources Conservation and Recovery Act (RCRA) and its amendments, are administered by the U. S. Environmental Protection Agency. Some administration and enforcement activities related to federal legislation have been delegated to California State agencies.

The California Legislature enacted legislation expanding efforts for ground water quality protection in California beyond federal requirements. The Legislature assigned several State agencies various responsibilities for investigation, mitigation, and control of ground water pollution and contamination.

The lead enforcement agency for most ground water quality protection issues in California is the State Water Resources Control Board (State Board) and the nine California Regional Water Quality Control Boards (Regional Boards). The State Board oversees the activities of the nine regional boards.

The Department of Health Services or, under some circumstances, the U. S. Environmental Protection Agency, is the lead enforcement agency for ground water quality issues related to hazardous wastes.

*The EPA, the Department of Health Services, and the State Board have adopted regulations or standards establishing monitoring requirements for "waste facilities". These regulations or standards include requirements for design and performance of monitoring wells that are often more stringent than standards in this bulletin.*

Other State government organizations concerned or directly involved with ground water quality assessment or protection in California include:

- Department of Conservation, Division of Oil and Gas,

- Department of Food and Agriculture,
- Integrated Waste Management Board, and,
- Department of Water Resources.

California cities, counties, and local water agencies are also involved with ground water quality assessment and protection.

The Division of Oil and Gas has authority and responsibility for geothermal wells and other special wells constructed in the State's Geothermal Resources Areas (pursuant to Chapter 4, Division 3, California Public Resources Code). Shallow wells drilled for geothermal observation are subject to regulations and standards established by DOG.

After July 17, 1991 the California Environmental Protection Agency will oversee the activities of the State Water Resources Control Board and the Integrated Waste Management Board. Some of the environmental protection activities of the Department of Health Services and the Department of Food and Agriculture will also come under the California Environmental Protection Agency.

### **Scope, Organization, and Limitations of Standards**

Certain standards that apply to water wells also apply to monitoring wells. Therefore the Monitoring Well Standards refer frequently to the Water Well Standards. Standards that apply only to monitoring wells, or that require emphasis, are discussed in detail in the Monitoring Well Standards. The Monitoring Well Standards are arranged in a format similar to the Water Well Standards.

These standards are not intended as a complete manual for monitoring well construction, alteration, maintenance, and destruction. These standards serve only as minimum statewide guidelines towards ensuring that monitoring wells do not constitute a significant pathway for the movement of poor quality water, pollutants, or contaminants. These standards provide no assurance that a monitoring well will perform a desired function. In most cases ground water monitoring practices and monitoring well performance, or functional requirements, fall under the purview of the various agencies mentioned earlier. *Ultimate responsibility for the design and performance of a monitoring well rests with the well owner and/or the owner's contractor, and/or technical representative(s).*

# STANDARDS

## Part I. General

### Section 1. Definitions<sup>1</sup>.

- A. Monitoring Well. The term "monitoring well" is defined in Section 13712 of the California Water Code as:  
    "...any artificial excavation by any method for the purpose of monitoring fluctuations in groundwater levels, quality of underground waters, or the concentration of contaminants in underground waters."
- B. Exploration Hole (or Boring). An uncased temporary excavation whose purpose is the immediate determination of hydrologic conditions at a site.
- C. Enforcing Agency. An agency designated by duly authorized local, regional, or State government to administer and enforce laws or ordinances pertaining to the construction, alteration, maintenance, and destruction of monitoring wells.

### Section 2. Application to Well Type.

These standards apply to all types of monitoring wells, except as prescribed in Sections 3, 4, and 5, below. Before a change in use of a well is made, any standards for the new use must be complied with.

### Section 3. Exemptions for Unusual Conditions.

Under certain circumstances the enforcing agency may waive compliance with these standards and prescribe alternate requirements. These standards may be waived where they are impractical or ineffective because of unusual conditions or would result in an unsatisfactory condition or well function. In waiving any of these standards the enforcing agency shall, if at all possible, require measures be implemented to provide the same or greater level of water-quality protection that would otherwise be provided by these standards.

### Section 4. Exclusions.

Most standards in Part II, "Monitoring Well Construction," page 41, do not apply to "exploration holes." However, provisions of Section 7, "Reports," below and Part III, "Destruction of Monitoring Wells," page 50, do apply directly to exploration holes.

Exploration holes for determining suitability of on-site domestic sewage disposal that are less than 10 feet in depth are exempt from the reporting and destruction requirements of these standards.

Large volume excavations for determining the suitability of on-site domestic sewage disposal, such as backhoe trenches, that exceed ten feet in depth are exempt from the requirements of Part III of these standards. However, such excavations shall be backfilled with the excavated material or other suitable fill material and the backfill compacted in lifts to attain at least 90 percent relative compaction in order to restore physical conditions in the excavation as much as possible. If a layer or layers of material that serve to impede the

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<sup>1</sup> Selected technical terms are defined in Appendix A, page 77.



movement of poor-quality water, pollutants and contaminants are penetrated by the excavation, they shall be reestablished to the degree possible to provide protection for underground waters, unless otherwise approved by the enforcing agency. In some cases it may be necessary to backfill all or a portion of the excavation with sealing material meeting these standards to reestablish natural barriers to the movement of poor-quality water, pollutants, and contaminants.

#### **Section 5. Special Standards.**

The enforcing agency may prescribe measures more stringent than standards presented here, where needed to protect public safety or protect water quality.

#### **Section 6. Responsible Parties.**

Pursuant to Section 13750.5 (Division 7, Chapter 10, Article 3) of the California Water Code; construction, alteration, and destruction of monitoring wells shall be performed by contractors licensed in accordance with the California Contractors' License Law (Division 3, Chapter 9, California Business and Professions Code), except where exempted by law. Construction, alteration, or destruction of monitoring wells to monitor hazardous waste facilities, other waste facilities, or underground storage tanks, shall be performed under the supervision of a California Registered Professional Engineer, California Registered Geologist, or California Certified Engineering Geologist, where specified by law.

#### **Section 7. Reports.**

Monitoring well construction, alteration, and destruction reports shall be completed on forms provided by the California Department of Water Resources. Other types of forms may be used for submission to the Department with the prior approval of the Department. The completed forms shall be submitted to the Department in accordance with relevant provisions of Sections 13750 through 13754 (Division 7, Chapter 10, Article 3) of the California Water Code. Information concerning completion and submission of well construction, alteration, and destruction reports is contained in *Guide to the Preparation of the Water Well Drillers Report*, Department of Water Resources, October 1977, or its latest revision.

## Part II. Monitoring Well Construction

### Section 8. Well Location With Respect to Pollutants and Contaminants, and Structures.

Monitoring wells are usually constructed to observe conditions at defined or required locations. Monitoring well locations are usually selected on the basis of known or expected hydrologic, geologic, and water quality conditions and the location of pollutant or contaminant sources. Monitoring wells frequently need to be located close to or within areas of pollution or contamination.

- A. Separation. Monitoring wells shall be located an adequate distance from known or potential sources of pollution and contamination, including those listed in Section 8 of the Water Well Standards, unless regulatory or legitimate data requirements necessitate they be located closer.
- B. Flooding and Drainage. Monitoring wells should be located in areas protected from flooding, if possible. Provisions for locating monitoring wells in areas of flooding and drainage are contained in Section 8 of the Water Well Standards.
- C. Accessibility. All monitoring wells shall be located an adequate distance from buildings and other structures to allow access for well maintenance, modification, repair, and destruction, unless otherwise approved by the enforcing agency.
- D. Disposal of Wastes When Drilling in Contaminated or Polluted Areas. Drill cuttings and wastewater from monitoring wells or exploration holes in areas of known or suspected contamination or pollution shall be disposed of in accordance with all applicable federal, State, and local requirements. The enforcing agency should be contacted to determine requirements for the proper disposal of cuttings and wastewater.

### Section 9. Sealing the Upper Annular Space.

The space between the monitoring well casing and the wall of the well boring, usually referred to as the "annular space," shall be effectively sealed to prevent it from being a preferential pathway for the movement of poor quality water, pollutants, and contaminants. Since monitoring wells are often constructed to obtain water from discrete intervals, a secondary purpose of the annular seal can be to isolate the well intake section or screen to one water-bearing unit. The annular seal can also serve to protect the structural integrity of the well casing and to protect the casing from chemical attack and corrosion. Because monitoring wells are often located close to, or within areas affected by pollutants and contaminants, an effective annular seal is often critical for the protection of ground water quality.

General discussion of sealing methods and requirements for monitoring wells is contained in Section 9, Section 13, and Appendix B, of the Water Well Standards. Special requirements for monitoring wells include the following:

- A. Minimum Depth of Annular Seal.
  - 1. Water quality monitoring wells and monitoring wells constructed in areas of known or suspected pollution or contamination. The annular space shall be sealed from the top of the filter pack or monitoring zone to ground surface, unless otherwise approved by the enforcing agency. The top of the filter pack or monitoring zone shall not extend into another water-bearing unit above the single water-bearing unit being monitored unless otherwise approved by the enforcing agency. The filter pack or monitoring zone shall not extend into any confining layers that overlie or underlie the unit to be moni-

tored, unless otherwise approved by the enforcing agency. The annular surface seal shall be no less than 20 feet in length.

Seal lengths less than 20 feet are permissible only if shallow zones will be monitored and approval has been obtained from the enforcing agency. If possible, special protection shall be provided where a reduced-length seal is used, as described in Section 8 of the Water Well Standards.

2. Other Monitoring Wells. The upper annular seal shall extend from ground surface to a minimum depth of 20 feet. An annular seal less than 20 feet in length is permissible if provisions in Item 1, above, are followed.
3. Sealing Off Strata. Additional annular sealing material shall be placed below the minimum depth of the upper annular seal, as is needed, to prevent the movement of poor-quality water, pollutants, and contaminants through the well to zones of good-quality water. Requirements for sealing off zones are in Section 13 of the Water Well Standards.
4. Shallow Water Level Observation Wells. Water level observation wells less than 15 feet in total depth that are used to assess root zone drainage in agricultural areas are exempt from an annular surface seal requirement, unless otherwise required by the enforcing agency.
5. Areas of Freezing. The top of the annular seal may be below ground surface in areas where freezing is likely. Such areas include those listed in Section 9 of the Water Well Standards. The top of the annular seal shall not be more than 4 feet below ground surface. The remainder of the space above the seal may be made an integral part of a vault, in accordance with Section 10, Subsection E, page 45, below.
6. Vaults. At the approval of the enforcing agency, the top of the annular seal and well casing can be below ground surface where traffic or other conditions require. In no case shall the top of the annular seal be more than 4 feet below ground surface.

The top of the annular seal shall contact a suitable, watertight, structurally-sound subsurface vault, or equivalent feature, that encloses the top of the well casing in accordance with Section 10, Subsection E, page 45, below. The vault shall extend from the top of the annular seal to at least ground surface.

B. Sealing Conditions.

1. Temporary Conductor Casing. If "temporary" conductor casing is used during drilling, it shall be removed during the placement of the casing and annular seal materials, as described in Section 9 of the Water Well Standards. If the temporary conductor casing "cannot" be removed, as defined in Section 9 of the Water Well Standards, sealing material shall be placed between the conductor casing and borehole wall, and between the well casing and conductor casing, in accordance with methods described in Section 9 of the Water Well Standards. Sealing material shall extend to at least the depths specified in Subsection A of this section.
2. Permanent Conductor Casing. If a permanent conductor casing is to be installed, the monitoring well borehole diameter shall be at least 4 inches greater than the outside diameter of the conductor casing. The inner diameter of the permanent conductor



casing shall in turn be at least 4 inches greater than the outside diameter of the well casing.

Sealing material shall be placed between the permanent conductor casing and the borehole wall, and the conductor casing and the well casing. The sealing material shall extend to at least the depths specified in Subsection A of this section.

- C. Radial Thickness of Seal. A minimum of two inches of sealing material shall be maintained between all casings and the borehole wall, within the interval to be sealed, except as noted in Section 9 of the Water Well Standards. At least two inches of sealing material shall also be maintained between all "casings" in a borehole, within the interval to be sealed unless otherwise approved by the enforcing agency. Additional space shall be provided, where needed, to allow casings to be properly centralized and spaced and allow the use of a tremie pipe during well construction (if required), especially for deeper wells.
- D. Sealing Material. Sealing material shall consist of neat cement, sand-cement, or bentonite clay. Cement-based sealing material shall be used opposite fractured rock, unless otherwise approved by the enforcing agency. Concrete shall be used only with the approval of the enforcing agency.

Sealing material shall be selected based on required structural, handling, and sealing properties, and the chemical environment into which it is placed. Used drilling mud or cuttings from drilling shall not be used for any part of sealing material.

- 1. Water. Water used for sealing mixtures should generally be of drinking water quality, shall be compatible with the type of sealing material used, shall be free of petroleum and petroleum products, and shall be free of suspended matter. Good-quality water is necessary to ensure that sealing materials achieve proper consistency for placement and achieve adequate structural and sealing properties.

Nonpotable water can sometimes be used for preparing cement-based sealing materials. In no case shall the concentration of chloride in water used in cement-based sealing material exceed 2,000 milligrams per liter. Sulfate shall not exceed 1,500 mg/l.

Water used for sealing material shall be chemically analyzed if unknown. Only drinking-quality water of known composition should be used for preparing sealing mixtures for monitoring wells to be used for sensitive water-quality determinations.

- 2. Cement-Based Sealing Materials. Discussion and standards for cement-based sealing materials are contained in Section 9 of the Water Well Standards. Special considerations that apply to monitoring wells are:
  - a. Additives. Care should be exercised in the use of special additives for cement-based sealing materials, such as those used for modifying cement setting times. Some additives could interfere with sensitive water quality determinations.
  - b. Cooling Water. In the case of water quality monitoring wells, care should be exercised in the use of circulating cooling water to protect plastic casing from heat build-up during setting of cement-based sealing materials. Water introduced and/or circulated in a well for cooling could interfere with water quality determinations.
- 3. Bentonite-Based Sealing Materials. Discussion and standards for bentonite-based sealing materials are contained in Section 9 of the Water Well Standards.



- E. Transition Seal. A bentonite-based transition seal, up to 5 feet in length, is often placed in the annular space to separate filter pack and cement-based sealing materials. The transition seal can prevent cement-based sealing materials from infiltrating the filter pack. A short interval of fine-grain sand, usually less than 2 feet in length, is often placed between the filter pack and the bentonite transition seal to prevent bentonite from entering the filter pack. Also, fine sand is sometimes used in place of bentonite as the transition seal material.

Fine-grain forms of bentonite, such as granules and powder, are usually employed for a transition seal if a transition seal is to be placed above the water level in a well boring. Coarse forms of bentonite, such as pellets and chips, are often used where a bentonite transition seal is to be placed below the water level.

Transition seals should be installed by using a tremie pipe or equivalent. However, some forms of bentonite may tend to bridge or clog in a tremie pipe.

Bentonite can be placed in the well annulus in dry form or as slurry for transition seals. Water should be added to the bentonite transition seal prior to the placement of cement-based sealing materials where the bentonite is dry in the borehole. Care should be exercised during the addition of water to the borehole to prevent displacing the bentonite.

Water should be added to bentonite at a ratio of about 1 gallon for every 2 pounds of bentonite to allow for proper hydration. Water added to bentonite for hydration or to make a slurry shall be of suitable quality and free of pollutants and contaminants.

Sufficient time should be allowed for bentonite transition seals to properly hydrate before cement-based sealing materials are placed. Normally, 1/2 to 1 hour is required for hydration to occur. Actual time of hydration is a function of site conditions.

The top of the transition seal shall be sounded to ensure that no bridging occurred during placement.

- F. Placement of Annular Seal Material. All loose cuttings and other obstructions shall be removed from the annular space before sealing materials are placed. Sealing may be accomplished by using pressure grouting techniques, a tremie pipe, or equivalent. Sealing materials shall be installed as soon as possible during well construction operations. Sealing materials shall not be installed by "free-fall" from the surface unless the interval to be sealed is dry and less than 30 feet deep.

Casing spacers shall be used within the interval(s) to be sealed to separate individual well casing strings from one another in a borehole of a nested monitoring well. The spacers shall be placed at intervals along the casing to ensure a minimum separation of 2 inches between individual casing strings. Spacers shall be constructed of corrosion-resistant metal, plastic, or other non-degradable material. Wood shall not be used as spacer material.

Any metallic component of a spacer used with metallic casing shall consist of the same material as the casing. Metallic spacer components shall meet the same metallurgical specifications and standards as the casing to reduce the potential for galvanic corrosion of the casing.

The spacing of casing spacers is normally dictated by casing materials used, the orientation and straightness of the borehole, and the method used to install the casing. Spacers shall not be more than 12 inches in length and shall not be placed closer than 10 feet apart along a casing string within the interval to be sealed, unless otherwise approved by the enforcing agency.

Casing spacers shall be designed to allow the proper passage and distribution of sealing material around casing(s) within the interval(s) to be sealed.

Additional discussion and standards for placement of the annular seal are contained in Section 9, Section 13, and Appendix B of the Water Well Standards.

#### Section 10. Surface Construction Features.

Surface construction features of a monitoring well shall serve to prevent physical damage to the well; prevent entrance of surface water, pollutants, and contaminants; and prevent unauthorized access.

- A. Locking Cover. The top of a monitoring well shall be protected by a locking cover or equivalent level of protection to prevent unauthorized access.
- B. Casing Cap. The top of a monitoring well casing shall be fitted with a cap or "sanitary seal" to prevent surface water, pollutants, or contaminants from entering the well bore. Openings or passages for water level measurement, venting, pump power cables, discharge tubing, and other access shall be protected against entry of surface water, pollutants, and contaminants.
- C. Flooding. The top of the well casing shall terminate above ground surface and known levels of flooding, except where site conditions, such as vehicular traffic, will not allow.
- D. Bases. Unless otherwise approved by the enforcing agency, a concrete base or pad shall be constructed around the top of a monitoring well casing at ground surface and contact the annular seal, unless the top of the casing is below ground surface as provided by Subsection E, below. The base shall be at least 4 inches thick and shall slope to drain away from the well casing. The base shall extend at least two feet laterally in all directions from the outside of the well boring, unless otherwise approved by the enforcing agency.

The base shall be free of cracks, voids, and other significant defects likely to prevent water tightness. Contacts between the base and the annular seal, and the base and the well casing must be water tight and must not cause the failure of the well casing or annular seal.

Where cement-based annular sealing material is used, the concrete base shall be poured before the annular seal has set, unless otherwise approved by the enforcing agency.

- E. Vaults. At the approval of the enforcing agency, the top of the well casing may be below ground surface because of traffic or other critical considerations. A structurally-sound watertight vault, or equivalent feature, shall be installed to house the top of a monitoring well that is below ground surface. The vault shall extend from the top of the annular seal to at least ground surface. In no case shall the top of the annular seal be more than 4 feet below ground surface.

The vault shall contact the annular seal in a manner to form a watertight and structurally sound connection. Contacts between the vault and the annular seal, and the vault and the well casing, if any, shall not fail or cause the failure of the well casing or annular seal.

Where cement-based annular seal materials are used, the vault shall be set into or contact the annular seal material before it sets, unless otherwise approved by the enforcing agency. If bentonite-based sealing material is used for the annular seal, the vault should be set into the bentonite before it is fully hydrated.

Cement-based sealing material shall be placed between the outer walls of the vault and the excavation into which it is placed to form a proper, structurally sound foundation for the vault, and to seal the space between the vault and excavation. Bentonite-based sealing material may be used between the vault and excavation at the approval of the enforcing agency.

Sealing material surrounding a vault shall extend from the top of the annular seal to ground surface, unless precluded in areas of freezing. If cement-based sealing material is used for both the annular seal and the space between the excavation and vault, the sealing material shall be placed in a "continuous pour." In other words, cement-based sealing material shall be placed between the vault and excavation and contact the cement-based annular seal before the annular seal has set.

The vault cover or lid shall be watertight but shall allow the venting of gases, unless otherwise approved by the enforcing agency. The lid shall be fitted with a security device to prevent unauthorized access. The lid shall be clearly and permanently marked "MONITORING WELL." The vault and its lid shall be strong enough to support vehicular traffic where such traffic might occur.

The top of the vault shall be set at or above grade so drainage is away from the vault. The top of the well casing contained within the vault shall be covered in accordance with requirements under Subsections A and B, above, so that water, contaminants, or pollutants that may enter the vault will not enter the well casing.

- F. Protection From Vehicles. Protective steel posts, or the equivalent, shall be installed around a monitoring well casing where it is terminated above ground surface in areas of vehicular traffic. The posts shall be easily seen and shall protect the well from vehicular impact.

Additional requirements for surface construction features are in Section 10 of the Water Well Standards.

#### Section 11. Filter Pack.

Monitoring well filter pack material shall consist of nonreactive, smooth, rounded, spherical, granular material of highly uniform size and known composition. Filter pack material shall not degrade or consolidate after placement. The grain-size of the filter pack shall be matched to the slot size of the well screen so that any movement of filter pack material into the well will be limited to prevent significant voids in the filter pack that could ultimately destabilize the annular seal.

Filter pack material shall be obtained from clean sources. Filter pack material should be washed and properly packaged for handling, delivery, and storage, if used in monitoring wells constructed for sensitive water quality determinations.

Care should be exercised in the storage of filter pack materials at a drilling site to ensure the material does not come into contact with pollutants or contaminants. Care should also be exercised to prevent the introduction of foreign substances, such as clay or vegetative matter, that might interfere with the placement and function of the filter pack.

Filter pack material shall be placed in the well boring by use of a tremie pipe or equivalent. The depth of the top of the filter pack shall be carefully checked and the volume of emplaced filter pack material verified to determine that filter pack materials have not bridged during installation.



## Section 12. Casing.

The term "casing" in its broadest sense includes all tubular materials that are permanent features of a well. Screens, collars, risers, liners, and blank casing in monitoring wells maintain the well bore and provide a passage for ground water level measurement and/or sample-collection devices.

Protective casing serves to prevent accidental or intentional damage to a well. Protective casing normally consists of heavy gauge metallic pipe placed over the portion of the well casing that extends above ground surface.

Conductor casing usually functions as a temporary means of shoring the walls of a well boring to allow drilling and the placement of well construction materials. If used, temporary conductor casing is usually driven into place during drilling and is withdrawn at the same time filter pack and annular seal materials are installed around the well casing. Sometimes conductor casing is left in place and is made a permanent feature of the completed well structure. Requirements for sealing permanent conductor casing in place are contained in Section 9.

For the purpose of these standards, the term "casing" applies to screens, collars, risers, and blank casing, and other specialized products used to maintain the well bore. General discussion and standards for casing materials are contained in Section 12 of the Water Well Standards. Special considerations that apply to monitoring well casing are described below:

### A. Casing Material.

1. Chemical Compatibility. Special consideration shall be given to the selection of casing materials for monitoring wells installed in environments that are chemically "hostile". The selected casing shall resist chemical attack and corrosion.

Special consideration should be given to the selection of casing materials for wells to be used for sensitive water-quality determinations. Chemical interaction between casing materials and pollutants, contaminants, ground water, filter pack material, and geologic materials could bias ground-water quality determinations.

2. Used Casing. Used casing may be acceptable in certain cases, at the approval of the enforcing agency.
3. Plastic and Steel Casing. Plastic and steel well casing materials are commonly used for monitoring wells. The principal plastics used for water-quality monitoring wells are thermoplastics and fluorocarbon resins.

Standards for thermoplastic well casing are in Section 12 of the Water Well Standards. The principal thermoplastic material used for water quality monitoring wells is polyvinyl chloride (PVC).

Fluorocarbon casing materials include fluorinated ethylene propylene (FEP) and polytetrafluoroethylene (PTFE). Fluorocarbon resin casing materials are generally considered immune to chemical attack. Fluorocarbon casing materials shall meet the following specifications, including the latest revisions thereof:

- a. ASTM D3296, *Standard Specification for FEP-Fluorocarbon Tube.*
- b. ASTM D3295, *Standard Specifications for PTFE Tubing.*

Stainless steel is the most common form of metallic casing used in monitoring wells constructed for sensitive water quality determinations. Stainless steel casing shall meet the provisions of ASTM A312, *Standard Specification for Seamless and Welded Austenitic Stainless Pipe*, and shall meet general requirements for tubular steel products in Section 12 of the Water Well Standards.

- B. Multiple Screens. Monitoring well casing strings shall not have openings in multiple water-bearing units (multi-level monitoring wells), if poor-quality water, pollutants, or contaminants in units penetrated by the well could pass through the openings and move to other units penetrated by the well and degrade ground water quality, unless otherwise approved by the enforcing agency.
- C. Bottom Plugs. The bottom of a monitoring well casing shall be plugged or capped to prevent sediment or rock from entering the well.
- D. Casing Installation. Discussion and standards for the installation of casing materials are in Section 12 of the Water Well Standards. Special considerations for monitoring wells are:
  - 1. Cleanliness. Casing, couplings, centralizers, and other components of well casing shall be clean and free of pollutants and contaminants at the time of installation.
  - 2. Joining Plastic Casing. Depending on the type of material and its fabrication, plastic casing shall be joined (threaded or otherwise coupled) in a manner that ensures its water tightness. Organic solvent welding cements or glues should not be used for joining plastic casing if glues or cement compounds could interfere with water-quality determinations.
  - 3. Impact. Casing shall not be subjected to significant impact during installation that may damage or weaken the casing.

### Section 13. Well Development.

Monitoring well development, redevelopment, and reconditioning shall be performed with care so as to prevent damage to the well and any strata surrounding the well that serve to restrict the movement of poor-quality water, pollutants, and contaminants. Development, redevelopment, and reconditioning operations shall be performed with special care where a well has been constructed in an area of known or suspected pollution or contamination. Such special care is necessary to prevent the spread of pollutants and contaminants in the environment and to protect public health and safety.

Water, sediment, and other waste removed from a monitoring well for "development" operations shall be disposed of in accordance with applicable federal, State, and local requirements. The enforcing agency should be contacted concerning the proper disposal of waste from development operations.

Appropriate methods of well development vary with the type and use of a monitoring well. Development methods that may be acceptable under certain circumstances include:

- A. Mechanical Surging. Plungers, bailers, surge blocks, and other surging devices shall incorporate safety valves or vents to prevent excessive pressure differentials that could damage casing or screen.

- B. Overpumping and Pump Surging. Overpumping and surging may not be suitable for development of wells producing large amounts of sediment because of the potential for clogging or jamming of pumps.
- C. Air Development. Some air development methods are not acceptable for monitoring wells to be used for sensitive water-quality determinations.
- D. Water Jetting. Water used in jetting operations shall be free of pollutants and contaminants. Water-jetting methods are not always acceptable for monitoring wells used for sensitive water-quality determinations.
- E. Chemical Development. Extreme care shall be exercised in the use of chemicals for monitoring well development. It is often unacceptable to use chemicals for developing monitoring wells to be used for water-quality determinations. Chemicals introduced for development shall be completely removed from the well, filter pack, and water-bearing strata accessed by the well immediately after development operations are completed.

The various methods described above are sometimes used in combination.

#### Section 14. Rehabilitation and Repair of Monitoring Wells.

For the purpose of these standards, "well rehabilitation" includes the treatment of a well to recover loss in yield caused by incrustation or clogging of the screen, filter pack, and/or water-bearing strata adjoining the well. Well rehabilitation methods that may, in certain cases, be acceptable for monitoring wells include mechanical surging, backwashing or surging by alternately starting or stopping a pump, surging with air, water jetting, sonic cleaning, chemical treatment, or combinations of these.

Rehabilitation methods shall be performed with care to prevent damage to the well and any barriers that serve to restrict the movement of poor-quality water, pollutants, or contaminants. Chemicals used for rehabilitation shall be completely removed from the well, filter pack, and water-bearing strata accessed by the well immediately after rehabilitation operations are completed. Chemicals, water, and other waste shall be disposed of in accordance with applicable federal, State, and local requirements. The enforcing agency should be contacted regarding the proper disposal of waste from rehabilitation operations.

Rehabilitation methods should be compatible with the use of the monitoring well. Special care should be given to the selection of rehabilitation methods for water-quality monitoring wells.

Materials used for repairing well casing shall meet the requirements of Section 12 of these standards.

#### Section 15. Temporary Cover.

The well or borehole opening and any associated excavations shall be covered at the surface to ensure public safety and to prevent the entry of foreign material, water, contaminants, and pollutants whenever work is interrupted by such events as overnight shutdown, poor weather, and required waiting periods to allow setting of sealing materials and the performance of tests. The cover shall be held in place or weighted down in such a manner that it cannot be removed except by equipment or tools.



### **Part III. Destruction of Monitoring Wells**

#### **Section 16. Purpose of Destruction.**

A monitoring well or exploration hole subject to these requirements that is no longer useful, permanently inactive or "abandoned" must be properly destroyed to:

- (1) Ensure the quality of ground water is protected, and,
- (2) Eliminate a possible physical hazard to humans and animals.

#### **Section 17. Definition of "Abandoned" Monitoring Well.**

A monitoring well is considered "abandoned" or permanently inactive if it has not been used for one year, unless the owner demonstrates intention to use the well again. In some cases regulatory agencies may require that an inactive monitoring well be maintained for future use.

In accordance with Section 24400 of the California Health and Safety Code, the monitoring well owner shall properly maintain an inactive well, as evidence of intention for future use, in such a way that the following requirements are met:

- "(1) The well shall not allow impairment of the quality of water within the well and ground water encountered by the well.
- (2) The top of the well or well casing shall be provided with a cover, that is secured by a lock or by other means to prevent its removal without the use of equipment or tools, to prevent unauthorized access, to prevent a safety hazard to humans and animals, and to prevent illegal disposal of wastes in the well. The cover shall be watertight where the top of the well casing or other surface openings to the well are below ground level, such as in a vault or below known levels of flooding. The cover shall be watertight if the well is inactive for more than five consecutive years. A pump motor, angle drive, or other surface feature of a well, when in compliance with the above provisions, shall suffice as a cover.
- (3) The well shall be marked so as to be easily visible and located, and labeled so as to be easily identified as a well.
- (4) The area surrounding the well shall be kept clear of brush, debris, and waste materials."

#### **Section 18. General Requirements.**

All permanently inactive or "abandoned" monitoring wells and exploration holes subject to these requirements shall be properly destroyed. The purposes of destruction are to eliminate the well structure and borehole as a possible means for the preferential migration of poor-quality water, pollutants, and contaminants; and, to prevent a possible hazard to humans and animals.

## Section 19. Requirements for Destroying Monitoring Wells and Exploration Holes.

General requirements for destroying monitoring wells and exploration holes are contained in Section 23 of the Water Well Standards. Special considerations for monitoring wells and exploration holes are as follows.

A. Monitoring Wells. Monitoring wells shall be destroyed in accordance with the following requirements and Section 23 of the Water Well Standards, irrespective of their original date of construction.

1. Preliminary Work. A monitoring well shall be investigated before it is destroyed to determine its condition and details of its construction. The well shall be sounded immediately before it is destroyed to make sure no obstructions exist that will interfere with filling and sealing.

The well shall be cleaned before destruction as needed so that all undesirable materials, including obstructions to filling and sealing, debris, oil from oil-lubricated pumps, or pollutants and contaminants that could interfere with well destruction, are removed for disposal.

The enforcing agency shall be notified as soon as possible if pollutants or contaminants are known or suspected to be present in a well to be destroyed. Well destruction operations may then proceed only at the approval of the enforcing agency. The enforcing agency should be contacted to determine requirements for proper disposal of all materials removed from a well to be destroyed.

2. Sealing Conditions. The following minimum requirements shall be followed when various conditions are encountered.

- a. The monitoring well casing, and any other significant voids within the well, shall, at a minimum, be completely filled with sealing material, if the following conditions exist:
  - The monitoring well is located in an area of known or potential pollution or contamination, and,
  - The well was constructed and maintained in accordance with these standards.

Sealing material may have to be placed under pressure to ensure that the monitoring well is properly filled and sealed.

- b. A monitoring well shall be destroyed by removing all material within the original borehole, including the well casing, filter pack, and annular seal; and the created hole completely filled with appropriate sealing material, if the following conditions exist:
  - The well is located in an area of known or potential pollution or contamination, and,
  - The well's annular seal, casing, screen, filter pack, or other components were not constructed or maintained according to these standards so that well destruction by merely filling the well casing with sealing material, as in "a" above, would not prevent potential water-quality degradation from



the movement of poor-quality water, pollutants, or contaminants through the destroyed well structure.

Material to be extracted from the original borehole shall be removed by means of drilling, including overdrilling, if necessary. The enforcing agency should be contacted to determine requirements for proper disposal of removed materials.

Casing, filter pack, and annular seal materials may be left in place during sealing operations, if the enforcing agency agrees they cannot or should not be removed. In such a case, appropriate sealing material shall be placed in the well casing, filter pack, and all other significant voids within the entire well boring. Casing left in place may require perforation or puncturing to allow proper placement of sealing materials. Sealing material may have to be applied under pressure to ensure its proper distribution.

- c. **Monitoring wells shall, at a minimum, be destroyed in accordance with the requirements of Section 23 of the Water Well Standards if located in an area free of any known or potential contamination or pollution.**

- B. **Exploratory Borings.** Exploratory borings shall be completely filled with appropriate sealing material from bottom to top, if located in areas of known or suspected contamination or pollution. Borings located outside such areas shall, at a minimum, be filled with sealing material from ground surface to the minimum depths specified in Section 23 of the Water Well Standards. Additional sealing material shall be placed below the minimum surface seal where needed to prevent the interchange of poor-quality water, pollutants, or contaminants between strata penetrated by the boring.

Appropriate fill or sealing material shall be placed below and between intervals containing sealing material. Sealing material is often economical to use as fill material.

The boring shall be inspected immediately prior to filling and sealing operations. All obstructions and pollutants and contaminants that could interfere with filling and sealing operations shall be removed prior to filling and sealing. The enforcing agency shall be notified as soon as possible if pollutants or contaminants are known or suspected to be in a boring to be destroyed. Well destruction operations may then proceed only at the approval of the enforcing agency. The enforcing agency should be contacted to determine requirements for proper disposal of removed materials.

- C. **Placement of Material.** The placement of sealing material for monitoring wells and exploratory borings is generally described in Section 23 and Appendix B of the Water Well Standards. The following additional requirements shall be observed when placing sealing material for monitoring well or exploratory boring destruction.

- 1. **Placement Method.** The well or exploratory boring shall be filled with appropriate sealing, and fill material where allowed, using a tremie pipe or equivalent, proceeding upward from the bottom of the well or boring.

Sealing material shall be placed by methods (such as the use of a tremie pipe or equivalent) that prevent freefall, bridging, and dilution of sealing materials, and/or prevent separation of aggregate from sealants. Sealing material may be placed by

freefall only where the interval to be sealed is dry and no more than 30 feet in depth. Fill material shall be placed by methods that prevent bridging and voids.

2. Timing of Placement. Sealing material shall be placed in one continuous operation (or "pour") from the bottom to the top of the well or boring, unless conditions in the well or boring dictate that sealing operations be conducted in a staged manner, and prior approval is obtained from the enforcing agency.
  3. Ground Water Flow. Special care shall be used to restrict the flow of ground water into a well or boring while placing sealing and fill material, if subsurface pressure producing the flow is significant.
  4. Sealing Pressure. Pressure required for the placement of cement-based sealing materials shall be maintained long enough for cement-based sealing materials to properly set.
  5. Verification. It shall be verified that the volume of sealing and fill material placed during destruction operations equals or exceeds the volume to be filled and sealed. This is to help determine whether the well or boring has been properly destroyed and that no jamming or bridging of the fill or sealing material has occurred.
- D. Sealing and Fill Materials. Materials used for sealing exploratory borings and monitoring wells shall have low permeabilities so that the volume of water and possible pollutants and contaminants passing through them will be of minimal consequence. Sealing material shall be compatible with the chemical environment into which it is placed, and shall have mechanical properties consistent with present and future site uses.

Suitable sealing materials include neat cement, sand-cement, and bentonite, all of which are described in Section 9 of these standards. Bentonite shall not be used as a sealing material opposite zones of fractured rock, unless otherwise approved by the enforcing agency. Drilling mud or drill cuttings are not acceptable as any part of sealing material for well destruction. Concrete may be used as a sealing material at the approval of the enforcing agency.

Fill material, if any, shall meet the requirements of Section 23 of the Water Well Standards. Fill material shall be free of pollutants and contaminants and shall not be subject to decomposition or consolidation after placement. Drilling mud or cuttings are not acceptable as any part of fill material.

- E. Additional Requirements for Monitoring Wells and Exploratory Borings in Urban Areas. The following additional requirements shall be met for destroying monitoring wells and exploratory borings in urban areas, unless otherwise approved by the enforcing agency:
1. The upper surface of the sealing material shall end at a depth of 5 feet below ground surface; and,
  2. If the well casing was not extracted during destruction and sealing operations, a hole shall be excavated around the well casing to a depth of 5 feet below ground surface after sealing operations have been completed and the sealing material has adequately set and cured. The exposed well casing shall then be removed by cutting the casing at the bottom of the excavation. The excavation shall be backfilled with clean, native soil or other suitable material.

- F. Temporary Cover. The well or borehole opening and any associated excavations shall be covered at the surface to ensure public safety and to prevent the entry of foreign material, water, pollutants, and contaminants; whenever work is interrupted by such events as overnight shutdown, poor weather, and required waiting periods to allow setting of sealing materials and the performance of tests. The cover shall be held in place or weighted down in such a manner that it cannot be removed, except by equipment or tools.

# CATHODIC PROTECTION WELLS

# CATHODIC PROTECTION WELL STANDARDS

## INTRODUCTION

Most wells in California are constructed to extract ground water, inject water, or monitor ground water conditions. Other, less common types of wells include cathodic protection wells. Cathodic protection wells, sometimes called "deep groundbeds," house devices to minimize electrolytic corrosion of metallic pipelines, tanks, and other facilities in contact with the ground.

### Electrolytic Corrosion

For the purpose of these standards, electrolytic corrosion is defined as the deterioration of metallic objects by electrochemical reaction with the environment. The electrolytic corrosion process is illustrated in Figure 4 for a metallic pipeline in a soil-water environment. This process gradually weakens the pipeline and can cause its failure.

In Figure 4, an electric potential is induced on the surface of the pipeline as a result of variations in the concentrations of salts in the soil and water surrounding the pipeline. This potential results in an electric current in the soil-water electrolyte. Current flows from an "anode area" on the pipeline to a "cathode area" on the pipeline. Metal is removed from the anode area by the current.

### Cathodic Protection

"Cathodic protection" is a term used for certain measures taken to prevent or minimize electrolytic corrosion of metallic equipment and structures. Cathodic protection devices redirect current to flow from a "sacrificial" anode to the soil-water electrolyte, instead of from an anode area on a pipeline or other metallic structure to be protected. The protective anode's role is to corrode in place of the metallic object it is designed to protect, as shown in Figure 5. The protected facility is made to be a permanent cathode by use of cathodic protection devices. Thus, the facility is said to be "cathodically protected."

Protective or sacrificial anodes can be placed close to ground surface or at significant depth. Anodes have been placed at shallow depths in horizontal and vertical arrays for many years. Shallow arrays are often not well suited for metropolitan areas because of land requirements, or suited for areas where electrical interference may be high.

Deep vertical anode installations, usually referred to as "cathodic protection wells," were first developed and used during the 1940s. They were developed in response to the constraints of shallow anode arrays.

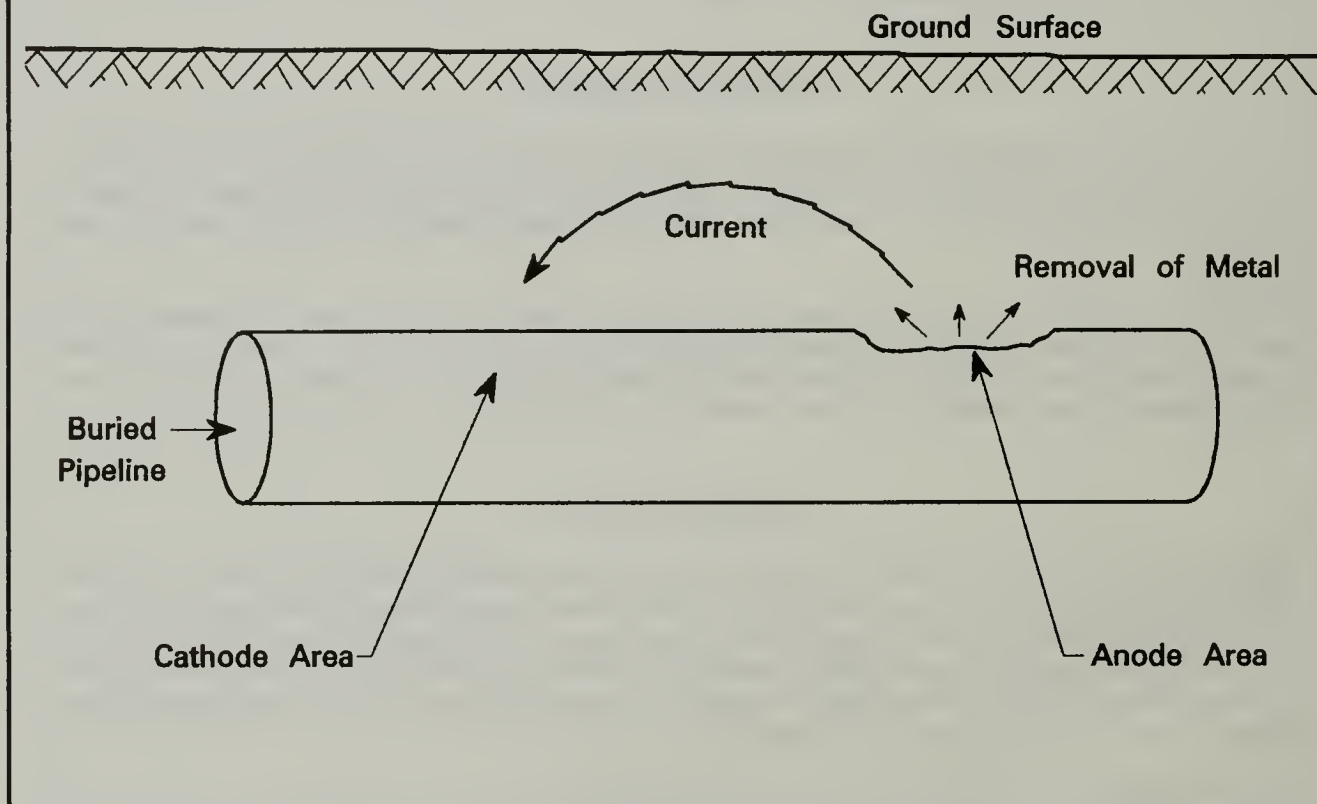
### Cathodic Protection Wells

Cathodic protection wells are widely installed to protect metallic objects in contact with the ground from electrolytic corrosion. Such objects include petroleum, natural gas, and water pipelines, and related storage facilities; power lines; telephone cables; and switchyards. Cathodic protection wells are sometimes used to control electrolytic corrosion in large water wells.



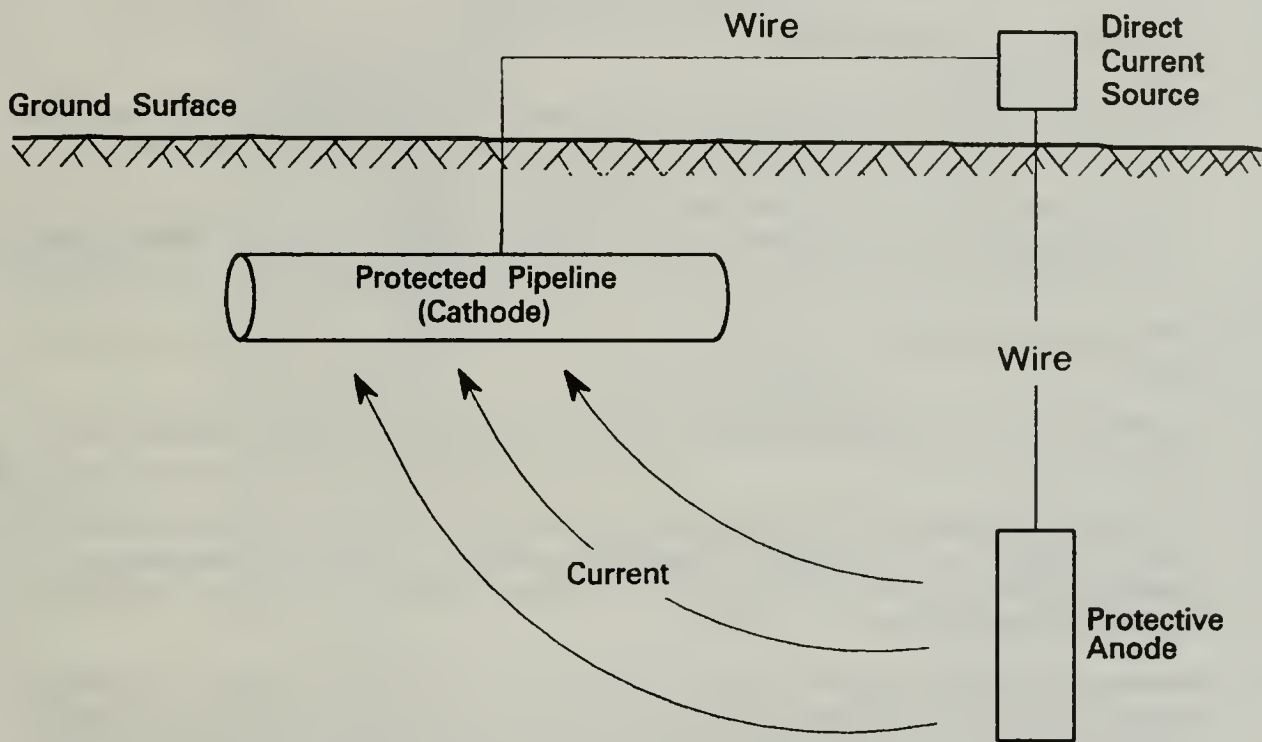
**Figure 4. ELECTROLYTIC CORROSION OF A BURIED PIPELINE**

(NOTE: Schematic, not to scale)



**Figure 5. CATHODIC PROTECTION OF A BURIED PIPELINE**

(NOTE: Schematic, not to scale)



Many cathodic protection wells have been constructed to protect pipelines that transport natural gas or other "hazardous" materials. The Natural Gas Pipeline Safety Act, Public Law 90-481 adopted by Congress in August 1968, provides requirements for cathodic protection of certain pipelines.

Most cathodic protection wells in California are located in areas where underground pipelines or "conveyance" systems are numerous and must be protected. These areas include:

- South coastal region from San Diego to Santa Barbara,
- Oil-producing areas of the southern San Joaquin Valley and the Central Coast, and,
- San Francisco Bay Area.

Few cathodic protection wells exist in California north of Sacramento.

Many cathodic protection wells, as illustrated in Figure 6, have been constructed by:

- (1) **Drilling a 6- to 12-inch diameter borehole to a desired depth.** Cathodic protection wells normally range from 100 to 500 feet in total depth. A few wells have been constructed to depths of 800 feet.

California Water Code Section 13711 defines a "cathodic protection well" as an anode installation exceeding 50 feet in depth. Installations less than 50 feet deep are "legally" considered "shallow anodes," not cathodic protection wells. Shallow anode installations are not specifically covered by these standards.

- (2) **Placing a string of anodes in the borehole within a designated interval, usually referred to as the "anode interval."**
- (3) **Backfilling the anode interval around the anodes with an electrically conductive material, such as granular coke.**
- (4) **Installing a small-diameter vent pipe that extends from the top of the anode interval to land surface, or above.** The purpose of the vent pipe is to release generated gases. Medium to large-diameter pipe or casing used in water wells to maintain the well bore and house pumping equipment is not normally used for cathodic protection wells.
- (5) **Backfilling the annulus between the vent pipe and borehole wall with an electrically non-conductive fill material to a specific height above the anode interval.** Such fill material usually consists of uniform, small-diameter gravel. Its purpose is to provide a permeable medium for migration of gases and to stabilize the walls of the borehole.

In the past this material was sometimes used to fill the annulus between the vent pipe and the borehole wall from the top of the anode interval to land surface. These standards require specific interval(s) of the upper annular space of a cathodic protection well be filled with sealing materials instead of gravel, to protect ground water quality.

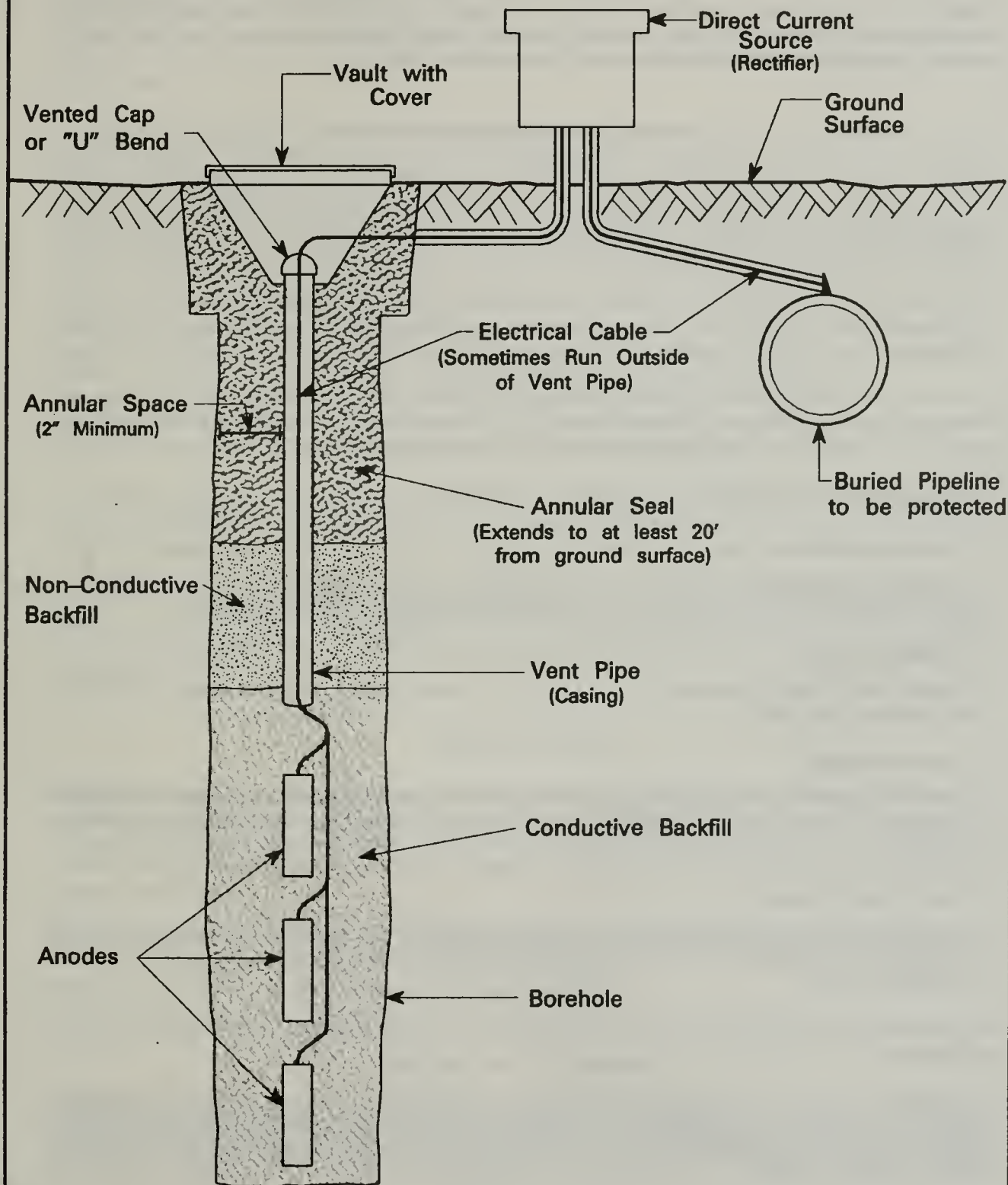
- (6) **Sealing the annulus between the vent pipe and the borehole wall, from the top of the non-conductive annular fill to land surface, with sealing material.**
- (7) **Installing a permanent cover over the well at ground surface.**
- (8) **Connecting the anode leads to the facility to be protected, possibly through an electrical current source.**

Individual designs of cathodic protection wells vary.



**Figure 6. CROSS SECTION OF A TYPICAL CATHODIC PROTECTION WELL**

(NOTE: Schematic, not to scale)



The protective anodes of a cathodic protection well usually corrode away with time. Thus a cathodic protection well's anodes determine the well's useful life. Anodes are usually designed to last 15 to 20 years.

There has been an increasing tendency to construct cathodic protection wells with large diameter vent pipe or casing so that anodes can be replaced through the casing. Anode replacement through casing eliminates the need to drill replacement wells when anodes have been expended.

### **Corrosion Coordinating Committees**

Serious electrical interference problems can occur where cathodic protection networks criss-cross one another or are too close to one another. Also, stray currents produced from electrical transmission lines and other equipment can sometimes interfere with the operation of cathodic protection systems. Interference problems are usually most pronounced in urban areas.

Corrosion control coordinating organizations have been formed in areas of California to overcome system interferences and other problems. Most organizations are affiliated with or are chapters of the National Association of Corrosion Engineers.

Corrosion control organizations represent the majority of utilities and other groups that install cathodic protection devices, including cathodic protection wells. Organization members coordinate the installation and operation of cathodic protection facilities with the goal of minimizing problems of electrical interference.

Four organizations that deal with Central and Southern California, are:

- **Southern California**

The Southern California Cathodic Protection Committee is a formal committee covering all of Southern California south of San Luis Obispo, Kern, and Inyo counties, except San Diego County.

- **San Diego County**

The San Diego County Underground Corrosion Control Committee is an informal organization that deals with the San Diego area.

- **Central California**

The Central California Cathodic Protection Committee is a formal committee covering all of Central California plus Sacramento Valley counties, and western Sierra Nevada mountain counties south of Plumas County.

- **San Francisco Bay Area**

The activities of the two committees that formerly covered the San Francisco Bay Area have been assumed by the San Francisco Section of the National Association of Corrosion Engineers. The committees were disbanded in 1985.

No coordinating organizations function in coastal counties north of San Francisco or in the northeastern part of the State.

Unfortunately, not all who install and operate cathodic protection facilities work with a corrosion coordinating organization. Those not associated with an organization are usually individuals or local agencies that are sometimes unaware of the existence of other installations. Non-coordinated facilities can seriously interfere with one another electrically.

## Need for Cathodic Protection Well Standards

Cathodic protection wells, along with other types of wells, can allow ground water quality degradation to occur. Improperly constructed or destroyed cathodic protection wells can constitute a preferential pathway for the movement of poor-quality water, pollutants, and contaminants. Cathodic protection wells constructed with gravel backfill to land surface are particularly conducive to the movement of poor-quality water, pollutants, or contaminants.

Water and electrolytes are sometimes introduced into cathodic protection wells through vent pipes, or gravel fill in the annulus, to keep wells functional where natural electrolytes are lacking. Such a practice could be considered "waste disposal" and may be illegal if poor-quality water is used.

Permanently inactive cathodic protection wells pose a threat for the movement of poor-quality water, pollutants, and contaminants, and should be properly destroyed. Permanently inactive cathodic protection wells are a threat to ground water quality because they become dilapidated with time, are sometimes forgotten, and are sometimes used for waste disposal.

Many cathodic protection wells have small diameter vent pipes that prevent entry by persons and most animals. However, large vent pipe sizes can pose a serious safety threat if left open at land surface.

## History of Cathodic Protection Well Standards

The California Legislature enacted legislation in 1949 directing the California Department of Water Resources to develop recommended water-quality protection standards for the construction and destruction of wells. The Legislature amended the Water Code in 1968 to require standards for cathodic protection wells.

Cathodic protection well standards for California were first published in 1973 as DWR Bulletin 74-1, *Cathodic Protection Well Standards: State of California*. Standards presented here replace those contained in Bulletin 74-1. Additional discussion on the history of well standards is contained in the "Introduction" section of this supplement (Bulletin 74-90) and Bulletin 74-81, *Water Well Standards: State of California*.

## Scope of Standards

The following are recommended minimum standards for construction, alteration, maintenance, and destruction of cathodic protection wells in California. They only serve as minimum guidelines toward ensuring cathodic protection wells do not constitute a significant pathway for movement of poor-quality water, pollutants, and contaminants. These standards do not ensure a cathodic protection well will perform its corrosion protection function adequately.

The functional requirements of cathodic protection wells may conflict with the application of certain standards for the protection of water quality. Consequently, some compromise has been made between well function and resource protection in the development of these standards.

## Organization of Standards

These standards are arranged in a format similar to the Water Well Standards. Since many of the standards that apply to water wells also apply to cathodic protection wells, many references are made in these standards to the Water Well Standards. Standards that apply only to cathodic protection wells or that require emphasis for cathodic protection wells, are discussed in detail in these standards.



# STANDARDS

## Part I. General

### Section 1. Definitions<sup>1</sup>.

- A. Cathodic Protection Well. A cathodic protection well is defined in Section 13711 of the California Water Code as:  

"...any artificial excavation in excess of 50 feet constructed by any method for the purpose of installing equipment or facilities for the protection electrically of metallic equipment in contact with the ground, commonly referred to as cathodic protection."
- B. Enforcing Agency. An agency designated by duly authorized local, regional, or State government to administer and enforce laws or ordinances pertaining to the construction, alteration, maintenance, and destruction of cathodic protection wells.
- C. Casing. All vent pipe, anode access tubing, electrical cable conduit, and other tubular materials that pass through the interval to be sealed.
- D. Conductor Casing. A tubular retaining structure temporarily or permanently installed in the upper portion of the well boring between the wall of the well boring and the inner well casing. Conductor casing is often installed to keep the borehole open during drilling if caving conditions are expected. Despite its title, conductor casing does not normally serve an "electrical" function for cathodic protection wells.

### Section 2. Exemptions Due to Unusual Conditions.

Under certain circumstances the enforcing agency may waive compliance with these standards and prescribe alternate requirements. These standards may be waived only where they are impractical or ineffective because of unusual conditions, or would result in unsatisfactory condition or well function. In waiving any of these standards, the enforcing agency shall, if at all possible, require that measures be implemented to provide the same or greater level of water-quality protection that would otherwise be provided by these standards.

### Section 3. Special Standards.

The enforcing agency may prescribe measures more stringent than standards described here, where needed to protect public safety or protect water quality.

### Section 4. Responsible Parties.

Corrosion control engineers are normally responsible for the design and supervision of corrosion control facilities incorporating cathodic protection wells. Pursuant to Section 13750.5 (Division 7, Chapter 10, Article 3) of the California Water Code, construction, alteration, and destruction of cathodic protection wells shall be performed by contractors licensed in accordance with the California Contractors' License Law

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<sup>1</sup> Technical terms are defined in Appendix A, page 77.

(Division 3, Chapter 9, California Business and Professions Code), except where exempted by law. Above-ground electrical facilities for cathodic protection wells should be installed by an appropriately licensed contractor.

#### Section 5. Reports.

Cathodic protection well construction, alteration, and destruction reports shall be completed on forms provided by the California Department of Water Resources. Other types of forms may be used for submission to the Department with the prior approval of the Department. The completed forms shall be submitted to the Department in accordance with relevant provisions of Sections 13750 through 13754 (Division 7, Chapter 10, Article 3) of the California Water Code. Information concerning completion and submission of well construction, alteration, and destruction reports is contained in *Guide to the Preparation of the Water Well Drillers Report*, Department of Water Resources, October, 1977, or its latest revision.

## Part II. Cathodic Protection Well Construction

### Section 6. Well Location With Respect to Pollutants and Contaminants, and Structures.

- A. Separation. Cathodic protection wells shall be located an adequate distance from known or potential sources of pollution or contamination, where site constraints and corrosion control considerations allow. Potential sources of pollution and contamination include those listed in Section 8 of the Water Well Standards.

As specified in Section 7 below, the length of the annular seal for a cathodic protection well shall be increased if the well is located in a congested urban area, or is located within 100 feet of any potential source of pollution or contamination.

- B. Flooding and Drainage. Cathodic protection wells should be located in areas protected from flooding, if possible. Wells located in areas of flooding shall be protected from flood waters and drainage, including protective measures outlined in Section 8, below.

Ground surface surrounding a cathodic protection well shall slope away from the well. Drainage from areas surrounding a cathodic protection well shall be directed away from the well.

- C. Accessibility. All cathodic protection wells shall be located an adequate distance from buildings and other structures to allow access for well maintenance, modification, repair, and destruction, unless otherwise approved by the enforcing agency.

### Section 7. Sealing the Upper Annular Space.

The space between the cathodic protection well casing and the wall of the well boring, often referred to as the "annular space," shall be effectively sealed to prevent it from being a preferential pathway for the movement of poor-quality water, pollutants, or contaminants. In some cases, secondary purposes of the annular seal are to stabilize the borehole wall, protect casing from degradation or corrosion, and ensure the structural integrity of the casing.

General discussion of sealing requirements and methods is contained in Section 9, Section 13, and Appendix B of the Water Well Standards. Special requirements for sealing cathodic protection wells are:

A. Minimum Depth of Annular Seal.

1. Minimum Depth. The annular space shall be filled with appropriate sealing material from ground surface to a depth of at least 20 feet below land surface. The annular space shall be sealed to a depth of at least 50 feet below land surface in congested urban areas, or where a cathodic protection well is within 100 feet of any potential source of pollution or contamination. Additional annular sealing material shall be installed to greater depths where adverse conditions exist that increase the risk of pollution or contamination of ground water.
2. Fill. Any annular space existing between the base of the annular surface seal and the top of the anode and conductive fill interval shall be filled with appropriate fill or sealing material. Fill material should consist of washed granular material such as sand, pea gravel, or sealing material. Fill material shall not be subject to decomposition or

consolidation after placement and shall be free of pollutants and contaminants. Fill material shall not contain drill cuttings or drilling mud. Sealing material is often more practical and economical to use for filling the annular space than granular material.

3. Sealing-Off Strata. Additional annular sealing material shall be placed below the minimum depth of the annular surface seal, as needed, to prevent the movement of poor-quality water, pollutants, and contaminants through the well to zones of good-quality water. Requirements for sealing off zones are in Section 10, below.
- B. Sealing Conditions. Requirements for sealing the annular space under varied conditions are detailed in Section 9, Subsection B of the Water Well Standards.
- C. Radial Thickness of Seal. A minimum of 2 inches of sealing material shall be maintained between all casings and the borehole wall within the interval to be sealed, except where temporary conductor casing cannot be removed as noted in Section 9 of the Water Well Standards. At least 2 inches of sealing material shall be maintained between all casings in a borehole, within the interval to be sealed unless otherwise approved by the enforcing agency. Additional space shall be provided, where needed, to allow casings to be properly centralized and spaced and allow the use of a tremie pipe during well construction (if required), especially for deeper wells.
- D. Sealing Material. Sealing material shall consist of neat cement, sand-cement, concrete, or bentonite clay as discussed in Section 9 of the Water Well Standards. Cement-based sealing material shall be used opposite zones of fractured rock used. Concrete shall only be used at the approval of the enforcing agency. Drill cuttings and used drilling mud shall not be used as any part of sealing material.
- E. Placement of Seal. Standards for the placement of annular seals are described in Section 9 and Appendix B of the Water Well Standards.

## Section 8. Surface Construction Features.

Surface construction features of a cathodic protection well shall serve to prevent physical damage to the well; prevent the entry of surface water, pollutants, and contaminants; and prevent unauthorized access.

- A. Locking Cover. The top of a cathodic protection well shall be protected by a locking cover or equivalent level of protection to prevent unauthorized access. All such covers shall allow the venting of gases.
- B. Casing Cap. The top of a cathodic protection well casing shall be fitted with a watertight cap, cover, "U" bend, or equivalent device to prevent the entry of water, pollutants, and contaminants into the well bore. All such covers shall allow venting of gases from the well.
- C. Flooding. The top of the well casing shall terminate above ground surface and known levels of flooding, except where site conditions, such as vehicular traffic, will not allow.
- D. Bases. A concrete base or pad shall be constructed around the top of a cathodic protection well casing at ground surface and contact the annular seal, unless the top of the casing is to be below ground surface as provided by Subsection E, below. The base shall be at least 4 inches thick and shall slope to drain away from the well casing. The base shall extend at least



2 feet laterally in all directions from the outside of the well boring, unless otherwise approved by the enforcing agency.

The base shall be free of cracks, voids, and other significant defects likely to prevent water tightness. Contacts between the base and the annular seal, and the base and the well casing must be water tight and must not cause the failure of the well casing or annular seal.

Where cement-based annular sealing material is used, the concrete base shall be poured before the annular seal has set, unless otherwise approved by the enforcing agency.

- E. Vaults. At the approval of the enforcing agency, the top of a cathodic protection well may be below ground surface because of traffic or other critical considerations. A watertight, structurally-sound vault, or equivalent feature, shall be installed to house the top of the well casing if it terminates below ground surface.

The vault shall extend from the top of the annular seal to at least ground surface. In no case shall the top of the annular seal be more than 4 feet below ground surface.

The vault shall contact the annular seal in a manner to form a watertight and structurally-sound connection. Contacts between the vault and the annular seal, and the vault and the well casing (if any), shall not fail, or cause the failure of the well casing or annular seal.

Where cement-based annular sealing materials are used, the vault shall be set into or contact the annular sealing material before it sets, unless otherwise approved by the enforcing agency. If bentonite-based sealing material is used for the annular seal, the vault shall be set into the bentonite before it is fully hydrated.

Cement-based sealing material shall be placed between the outer walls of the vault and the excavation into which it is placed to form a proper, structurally sound foundation for the vault, and to seal the space between the vault and excavation.

Sealing material surrounding the vault shall extend from the top of the annular seal to ground surface, unless precluded in areas of freezing. If cement-based sealing material is used for both the annular seal and the space between the excavation and vault, the sealing material shall be emplaced in a "continuous pour." In other words, cement-based sealing material shall be placed between the vault and excavation and contact a cement-based annular seal before the annular seal has set.

The vault cover or lid shall be watertight but shall allow the venting of gases. The lid shall be fitted with a security device to prevent unauthorized access and shall be clearly and permanently labeled "CATHODIC PROTECTION WELL." The vault and its lid shall be strong enough to support vehicular traffic where such traffic might occur.

The top of the vault shall be set at grade, or above, so that drainage is away from the vault. The top of the casing contained within the vault shall be capped in accordance with requirements of Subsection B, above so that water, contaminants, and pollutants that may enter the vault will not enter the well casing.

- F. Protection From Vehicles. Protective steel posts, or the equivalent, shall be installed around a cathodic protection well casing where it is terminated above ground surface in areas of vehicular traffic. The posts shall be easily seen and shall protect the well from vehicular impact.



Additional requirements for surface construction features are contained in Section 10 of the Water Well Standards.

### **Section 9. Casing.**

Vent pipe, anode access tubing, and any other tubular materials that pass through the interval to be filled and sealed are all considered casing for the purpose of these standards. Materials used for cathodic protection well casing generally shall meet the requirements for casing materials and their installation in Section 12 of the Water Well Standards. Variance from the standards shall be at the approval of the enforcing agency. It is recommended that practices prescribed by the National Association of Corrosion Engineers also be followed in the design and installation of gas vents and electrical conduit.

Cathodic protection well casing should be at least 2 inches in internal diameter to facilitate eventual well destruction.

### **Section 10. Sealing-Off Strata.**

If a cathodic protection well penetrates a stratum or strata below the minimum required annular surface seal depth specified in Section 7, above and that stratum contains poor-quality water, pollutants, or contaminants that could mix with and degrade water contained in other strata penetrated by the well, additional annular sealing material shall be placed below the minimum required annular surface seal to prevent mixing and water-quality degradation.

The following minimum requirements shall be observed for isolating zones containing poor-quality water, pollutants, or contaminants for various cases:

Case 1. Upper Stratum. If a stratum containing poor-quality water, pollutants, or contaminants lies above a stratum to be protected, annular seal material shall extend from the top of the stratum containing the poor-quality water, pollutants, or contaminants down to at least 10 feet into the confining layer separating the two strata, or through the entire thickness of the confining layer, whichever is least.

Case 2. Lower Stratum. If a stratum containing poor-quality water, pollutants, or contaminants lies below a stratum to be protected, the annular space opposite the stratum to be protected shall be sealed along its full length. The seal shall extend at least 10 feet into the confining layer separating the two strata, or through the entire thickness of the confining layer, whichever is least.

#### Case 3. Multiple Strata.

- a. Where two or more strata containing poor-quality water, pollutants, or contaminants are adjacent to one another and overlie a stratum to be protected, the annular space opposite the strata containing poor-quality water, pollutants, or contaminants and opposite all interbedded confining layers shall be sealed. The annular seal shall extend at least 10 feet down into, or completely through, whichever is least, the confining layer separating the strata containing poor-quality water, pollutants, or contaminants and the underlying stratum to be protected.
- b. Where two or more strata containing poor-quality water, pollutants, or contaminants underlie a stratum to be protected, the annular space opposite the stratum to be protected shall be sealed. The seal shall continue down at least 10 feet into, or completely through, whichever is least, the confining layer separating the stratum to be protected and the underlying strata containing poor-quality water, pollutants or contaminants.

- c. **Where two strata containing poor-quality water, pollutants, or contaminants are separated by a stratum to be protected, the annular space opposite the stratum to be protected, the confining strata underlying and overlying the stratum to be protected, and the upper stratum containing poor-quality water, pollutants, or contaminants shall be sealed off.**

The supplementary seals described in the cases above shall be extended up to and contact the base of the required minimum annular surface seal described in Section 7 above, if they are otherwise required to be within 10 feet of the surface seal. Sealing the entire annulus above the anode interval will often economically fulfill the conditions outlined above.

Requirements for sealing materials and their placement are described in Section 7, above.

#### **Section 11. Repair of Cathodic Protection Wells.**

Materials used for repairing cathodic protection well casing shall meet the requirements of Section 9, above.

#### **Section 12. Temporary Cover.**

The well or borehole opening and any associated excavations shall be covered at the surface to prevent the entry of foreign material, water, pollutants, and contaminants, and to ensure public safety whenever work is interrupted by such events as overnight shutdown, poor weather and required waiting periods to allow setting of sealing materials and the performance of tests. The cover shall be held in place or weighted down in such a manner that it cannot be removed except by equipment or tools.

## Part III. Destruction of Cathodic Protection Wells

### Section 13. Purpose of Destruction.

A cathodic protection well that is no longer useful, permanently inactive or "abandoned" must be properly destroyed to:

- (1) Ensure the quality of ground water is protected, and,
- (2) Eliminate a possible physical hazard to humans and animals.

### Section 14. Definition of "Abandoned" Cathodic Protection Well.

A cathodic protection well is considered "abandoned" or permanently inactive when its anodes are exhausted and cannot, or will not, be replaced. A cathodic protection well is also considered "abandoned" or permanently inactive if it has not been used for one year, unless the owner demonstrates intention to use it again. To provide evidence of intention for future use of a well, the well owner, in accordance with Section 24400 of the Health and Safety Code, shall maintain the well in such a way that the following requirements are met:

- "(1) The well shall not allow impairment of the quality of water within the well and ground water encountered by the well.
- (2) The top of the well or well casing shall be provided with a cover, that is secured by a lock or by other means to prevent its removal without the use of equipment or tools, to prevent unauthorized access, to prevent a safety hazard to humans and animals, and to prevent illegal disposal of wastes in the well. The cover shall be watertight where the top of the well casing or other surface openings to the well are below ground level, such as in a vault or below known levels of flooding. The cover shall be watertight if the well is inactive for more than five consecutive years. A pump motor, angle drive, or other surface feature of a well, when in compliance with the above provisions, shall suffice as a cover.
- (3) The well shall be marked so as to be easily visible and located, and labeled so as to be easily identified as a well.
- (4) The area surrounding the well shall be kept clear of brush, debris, and waste materials."

### Section 15. General Requirements.

All permanently inactive or "abandoned" cathodic protection wells shall be properly destroyed. The purpose of destruction is to prevent a possible safety hazard to humans and animals and to eliminate the well structure as a possible means for the preferential migration of poor-quality water, pollutants, and contaminants.

### Section 16. Requirements for Destroying Cathodic Protection Wells.

General requirements for well destruction are contained in Section 23 of the Water Well Standards. Special considerations for cathodic protection wells are as follows:

- A. Preliminary Work. A cathodic protection well shall be investigated before it is destroyed to determine its condition, details of its construction and whether conditions exist that will interfere with filling and sealing.



The well shall be sounded immediately before it is destroyed to make sure that no obstructions exist that will interfere with filling and sealing. The well shall be cleaned before destruction, as needed, to ensure that all undesirable materials, including obstructions to filling and sealing, debris, and pollutants and contaminants that could interfere with well destruction are removed for disposal. The enforcing agency shall be notified as soon as possible if pollutants and contaminants are known or suspected to be in a well to be destroyed. Well destruction operations may then proceed only at the approval of the enforcing agency. The enforcing agency should be contacted to determine requirements for proper disposal of materials removed from a well to be destroyed.

B. Filling and Sealing Conditions. The following minimum requirements shall be followed when various conditions are encountered.

1. Wells that only penetrate unconsolidated material and a single "zone" of ground water. At a minimum, the upper 20 feet of the well casing and the annulus between the well casing and borehole wall (if not already sealed) shall be completely sealed with suitable material. Sealing material shall extend to a minimum depth of 50 feet below land surface if the well to be destroyed is located in an urban area, or is within 100 feet of any potential source of pollution or contamination. Additional sealing material may be needed if adverse conditions exist. The remainder of the well below the minimum surface seal shall be filled with suitable granular fill material, such as clean sand or pea gravel, or with sealing material.
2. Wells that penetrate several water-bearing strata. The upper portion of the well casing and annular space shall be filled with sealing material as described in Item 1, above. Strata encountered below the surface seal that contain poor-quality water, pollutants, or contaminants that could mix with and degrade water in other strata penetrated by the well, shall be effectively isolated by sealing the well bore and annulus within intervals specified in Section 10, above. The remainder of the well shall be filled with suitable granular fill or sealing material.
3. Wells penetrating fractured rock. Sealing material shall be installed as outlined in Items 1 and 2, above. Cement-based sealing material shall be used opposite fractured rock. The remainder of the well shall be filled with fill or sealing material, as appropriate.
4. Wells in nonfractured consolidated strata. Sealing material shall be installed as outlined in Items 1 and 2, above. The remainder of the well shall be filled with fill or sealing material, as appropriate.
5. Wells penetrating water-bearing zones or aquifers of special significance. The enforcing agency may require that specific water-bearing zones be sealed off for well destruction.

C. Placement of Material. The placement of sealing materials for cathodic protection well destruction is generally described in Section 23 and Appendix B of the Water Well Standards. The following additional requirements shall be observed in destroying cathodic protection wells.

Casing, cables, anodes, granular backfill, conductive backfill, and sealing material shall be removed as needed, by redrilling, if necessary, to the point needed to allow proper placement of sealing materials within required sealing intervals. Removal of some or all well materials will likely be required for cathodic protection wells that were not constructed in accordance with

these standards, or standards adopted by the Southern California Cathodic Protection Committee in December 1969.

Casing that cannot be removed shall be adequately perforated or punctured at specific intervals to allow pressure injection of sealing materials into granular backfill and all other voids that require sealing.

The following requirements shall be observed in placing fill and sealing material in cathodic protection wells to be destroyed.

1. Placement Method. The well shall be filled and sealed with appropriate material upward from the bottom of the well using a tremie pipe or equivalent.  
  
Sealing material shall be placed by methods (such as by the use of a tremie pipe or equivalent) that prevent freefall, bridging, or dilution of the sealing materials, or separation of aggregates from sealants. Sealing materials shall not be installed by freefall unless the interval to be sealed is dry and no deeper than 30 feet below ground surface.
  2. Timing of Placement. Sealing material shall be placed in one continuous operation (or "pour") from the bottom to the top of the well unless conditions in the well dictate that sealing operations be conducted in a staged manner and prior approval is obtained from the enforcing agency.
  3. Ground Water Flow. Special care shall be used to restrict the flow of ground water into a well while fill and sealing material is being placed, if subsurface pressure causing the flow of water is significant.
  4. Sealing Pressure. Pressure required for placement of cement-based sealing material shall be maintained long enough for the cement-based sealing material to set.
  5. Verification. Verification shall be made that the volume of sealing and fill material placed in a well during destruction operations equals or exceeds the volume to be filled and sealed. This is to help determine that the well has been properly destroyed and that no jamming or bridging of the fill or sealing material has occurred.
- D. Sealing Materials. Materials used for sealing cathodic protection wells for destruction shall have low permeabilities so that the volume of water and possible pollutants and contaminants passing through them will be of minimal consequence. Sealing material shall be compatible with the chemical environment into which it is placed and shall have mechanical properties compatible with present and future site uses.
- Suitable sealing materials include neat cement, sand-cement, concrete, and bentonite, as described in Section 9 of the Water Well Standards. Sealing materials used for isolating zones of fractured rock shall be cement-based, as described in Subsection B, above. Drilling mud or drill cuttings shall not be used as any part of a sealing material for well destruction. Concrete may be used as a sealing material at the approval of the enforcing agency.
- E. Fill Material. Many fill materials are suitable for destruction of cathodic protection wells. These include clean, washed sand or gravel or sealing material. Fill material shall be free of pollutants and contaminants and shall not be subject to decomposition or consolidation after placement. Fill material shall not contain drilling mud or cuttings.

- F. Additional Requirements for Destruction of Cathodic Protection Wells in Urban Areas. The following additional requirements shall be met at each well site in urban areas, unless otherwise approved by the enforcing agency:
- (1) The upper surface of the sealing material shall end at a depth of 5 feet below ground surface, and,
  - (2) If the casing was not extracted during destruction and sealing operations, a hole shall be excavated around the well casing to a depth of 5 feet below ground surface after sealing operations have been completed and sealing materials have adequately set and cured. The exposed well casing shall then be removed by cutting the casing at the bottom of the excavation. The excavation shall then be backfilled with clean, native soil or other suitable material.
- G. Temporary Cover. The well borehole and any associated excavations shall be covered at the surface to prevent the entry of foreign material, water, pollutants, and contaminants and to ensure public safety whenever work on the well is interrupted by such events as overnight shutdown, poor weather, and required waiting periods to allow setting of sealing materials and performance of tests. The cover shall be held in place or weighted down in such a manner that it cannot be removed except by equipment or tools.

## APPENDICES

# APPENDIX A

## Definition of Terms

**Protective Anode** - A metallic object designed to corrode in place of the object it is designed to protect.

**Cathodic Protection**<sup>1</sup> - A technique to prevent the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

**Cement, Portland Cement** - A cement that contains oxides of calcium, aluminum, iron, and silicon made by heating a mixture of limestone and clay in a kiln and pulverizing the resultant clinker, as defined in ASTM C150. Portland cement is also considered a hydraulic cement, because it must be mixed with water to form a cement-water paste with the ability to develop strength and harden, even under water.

**Centralizer** - A device that assists in centering tubular materials in a borehole.

**Conductance, Specific** - A measure of the ability of water to conduct electric current at 77 degrees Fahrenheit. It is related to the total concentration of ions in the water.

**Corrosion**<sup>1</sup> - The deterioration of a material, usually a metal, because of a reaction with its environment.

**Drilling Fluid** - A fluid (liquid or gas) used in drilling operations to remove cuttings from a borehole, to clean and cool the drilling bit, to reduce friction between the drill stem and the borehole wall, and, in some cases, to prevent caving or sloughing of the borehole.

**Electrolyte**<sup>1</sup> - A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field. The term electrolyte refers to the soil or liquid adjacent to, and in contact with a buried or submerged metallic structure including the moisture and other chemicals contained therein.

**Interference**<sup>1</sup> - The situation that arises when a foreign substructure is affected in any way by a direct current source.

**Rectifier**<sup>1</sup> - An electronic device that changes alternating current to direct current.

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<sup>1</sup> Definition from National Association of Corrosion Engineers Standard RP-01-69 or RP-05-72.



# APPENDIX B

## REFERENCES

Since Bulletin 74-81 was published in mid-1981 several new or revised publications have been issued that address ground water or well construction. This appendix lists publications issued or revised since 1981 and selected other publications that were reviewed during the preparation of this supplement. Publications that were used for Bulletin 74-81 that have since been revised are identified by a number in parentheses. These numbers refer to the publication's original position in the bibliography of Bulletin 74-81 (Appendix E, page 83).

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## Laws, Rules and Regulations

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  - California Health and Safety Code
  - California Public Resources Code
  - California Water Code
- B. The State Water Resources Control Board Model Water Well Ordinance.
- C. Existing ordinances of the counties of California pertaining to the construction, alteration, and destruction of wells.
- D. Laws, regulations, and recommendations of the various states pertaining to the construction, alteration, or destruction of wells.