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Initial Research into the Effects of Woody Vegetation on Levees

Volume IV of IV: Summary of Results and Conclusions

Maureen K. Corcoran, John F. Peters, Joseph B. Dunbar, Jose L. Llopis, Fred T. Tracy, Johannes L. Wibowo, Janet E. Simms, Christopher E. Kees, S. Kyle McKay, J. Craig Fischenich, Matthew W. Farthing, M. Eileen Glynn, Bryant A. Robbins, Ryan C. Strange, Martin T. Schultz, Joan U. Clarke, Thomas E. Berry, Charles D. Little, and Landris T. Lee

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Executive Summary

At the request of Headquarters, USACE (HQUSACE), in July 2007, the U.S. Army Engineer Research and Development Center (ERDC) conducted an extensive literature review focusing on the effects of woody vegetation on levees. The review indicated that minimal data exist on the scientific relationship between levees and woody vegetation. Because of the lack of scientific data, HQUSACE concluded that without further research, scientific questions regarding the effects of woody vegetation on levees would remain unanswered. In April 2008, HQUSACE requested that ERDC begin research on this issue. ERDC formed a team consisting of scientists and engineers with geotechnical, environmental, geological, biological and geophysical expertise to assess the impact of woody vegetation on the structural performance of earthen levees using scientific and engineering methods.

The ERDC team prepared a scope of work (SOW) to study the effect of living woody vegetation on slope stability, seepage analyses were used to assess changes in hydraulic conductivity and the effects of the initiation of internal erosion. These particular topics were selected based on input from federal and state agencies, which showed that directing the research toward the effects of woody vegetation on slope stability and internal erosion would advance the understanding of the interaction of roots within an engineered levee. However, the selection of slope stability and seepage for this research does not diminish the need for future research on other topics related to the effects of woody vegetation on levees. Rather, this study should be viewed as an initial research effort into a very complex issue.

This study consists of the following three interrelated components:

1. Site visits, field data collection, and laboratory testing to obtain pertinent information necessary to support subsequent modeling and simulation efforts.
2. Modeling and simulation of the engineering, geological and environmental conditions, and structural performance of the levee system, relative to the initiation of internal erosion and slope stability, under various loading conditions.

3. Developing results and conclusions regarding engineering impacts living of woody vegetation on slope stability and internal erosion.

Site investigations identified root system characteristics using geophysical survey methods, root excavation methods, and root strength (pull-out) tests. Root studies focused on living, healthy woody vegetation. Data collected by these methods were used in the seepage and slope stability analyses. One of the major findings from field investigations was the relative efficacy of electrical resistivity imaging (ERI) measurements in determining the size and extent of tree root balls, relative to other geophysical methods, such as ground penetrating radar (GPR) or electromagnetic (EM) techniques. Root excavation proved successful for validating GPR in sandy soils.

In addition to identifying root characteristics, field studies included soil permeameter testing for the purpose of calculating hydraulic conductivity to test the hypothesis that tree roots influence soil hydraulic properties. Permeameter tests were performed within the root system and in a nearby control area without a tree but within the same soil horizon. Soil samples were retrieved during permeameter testing for soil classification. Statistical methods were used to calculate and compare the mean values of the two data sets: root system versus the control area. The resulting mean values were not used directly in the model simulations because the modeling was performed prior to the field data collection. However, for consistency the resulting means and ranges of calculated hydraulic conductivities were compared to those found in the site engineering documents as well as the values used for seepage models. The statistical comparison of means did not produce conclusive evidence that tree roots influence the average hydraulic conductivity of a soil layer. Only one test showed evidence of an existing macropore associated with a tree site. These analyses were conducted for Sacramento, CA; Burlington, WA; Portland, OR; Lewisville, TX; Vicksburg, MS; Albuquerque, NM; Boca Raton, FL, and Danville, PA.

Slope stability models and seepage models used both two-dimensional (2-D) and three-dimensional (3-D) finite element computer codes. The stability analysis uses limit equilibrium methods for 2-D analyses and deformational analyses in three dimensions. Seepage models included analysis for internal erosion.

The ERDC research used SEEP2D for three analysis in the seepage analyses. These analyses included conducting a sensitivity analysis for hydraulic conductivity as it affects the groundwater flow field, producing a random macropore heterogeneity in a block of soil representing a root system, and representing a root as a defect extending from the surface to the base of the blanket. The extended root system was depicted as a uniform area of low hydraulic conductivity, which is an extreme representation that may not reflect actual field conditions. The results from these analyses are specific only to the levees studied for this research.

In the first approach, extensive 2-D sensitivity analyses were performed where the hydraulic conductivity of the woody vegetation zone was systematically varied from the surrounding soil by a factor of β, ranging from 1,000 to 0.001. When β is equal to 1.0, the analysis simulates a levee without woody vegetation. In these analyses, the woody vegetation (tree) zone was modeled as a continuum of porous media with dimensions 6 ft wide by 5 ft deep. Various hydraulic loadings were also applied in the sensitivity analyses using steady state and transient conditions.

Sensitivity analyses also investigated the influence of woody vegetation location on model output. Simulations included woody vegetation zones located at the levee toe, beyond the levee toe, levee slope, and levee crest on both the riverside and landside of the studied levees. Pore pressure and the phreatic surface from the seepage analysis were used in the slope stability model to determine effective stresses for strength computations. Two-dimensional analyses were conducted for Sacramento, CA; Burlington, WA; Portland, OR; and Albuquerque, NM.

The second seepage analysis recognized the heterogeneity of macropores within both a root system and surrounding soil matrix by randomly distributing hydraulic conductivity throughout the rectangular configuration representing a root system. Velocity vectors show that a random heterogeneous zone can have flow paths that support large flow velocities. However, research does not exist on whether high velocities result in the initiation of internal erosion.

The third approach in the seepage analysis considers the probability of a tree root creating a seepage exit thereby initiating internal erosion in the soil foundation. This analysis follows the procedure described by Schaefer et al. (2010). Results from this analysis are specific only to the levees studied for this research. Because of the complexity of processes related to seepage and piping and the lack of research supporting such processes, only the initiation of processes leading to internal erosion is addressed in this research. Analyses were conducted for Burlington, WA, Portland, OR, and Albuquerque, NM. Based on these analyses, the probability of initiation of internal erosion is negligible from woody vegetation at the toe of the levee for the Burlington and Portland sites. The results for Albuquerque yielded a factor of safety slightly higher than 1.0 but the probability of internal erosion occurring is negligible to 0.25.

Two-dimensional stability analyses were conducted using the Spencer Limit Equilibrium Method available within the UTEXAS4 slope stability software. Fixed input parameters for the analysis were soil properties, levee geometry, and root properties. Root reinforcement properties were derived from field test data collected by ERDC for this research. Variable input parameters included: tree position on the levee slope, tree weight, pore pressure, phreatic surface, river elevation, wind load, and failure criteria. In a simplified slope stability analysis, effective stresses for strength is to use the phreatic surface from the seepage analysis, and rather than using the pore pressures computed in the finite element analysis, an assumption is made as to what the pore pressures are below the phreatic surface. However, in the ERDC study, an accurate method of using pore pressures, as computed from the seepage flow analysis, in the slope stability analysis is used. Tree weights and wind loads are divided by 6 based on the 6-ft width because only one foot-wide slice is considered. Because tree root growth is variable, even for a given species in the same region, the root extent used in the models was varied to accommodate the inconsistent patterns of root growth. In general, this study observed that trees on the upper part of the slope decreased the factor of safety because they add weight. Trees near the toe increased the factor of safety because of the reinforcing effects of the roots and the increased counterweight effect of the tree to slope movement. Trees at midslope had lesser effect on the factor of safety because they acted as a load, but not a counterweight, and the roots are too shallow to reach the failure zone within the midslope region.

The objectives of the 3-D seepage and stability analyses were to validate the results of the more simplified 2-D model simulation. The 2-D model geometry and material properties of the woody vegetation zone were imported into the 3-D model. These analyses were made for the Sacramento, CA, and Burlington, WA, sites. The 3-D model modified the geometry to include three woody vegetation zones located at the toe (landside toe, Sacramento; riverside toe, Burlington) and positioned 20 ft apart, thereby creating a 3-D version of the 2-D model simulating a row of trees. Only steady state simulations were considered. Local 3-D effects were observed in the flow field around the zones, but resulted change was not apparent to the global flow field, location of the seepage face, or pore pressure gradients. The lack of change is attributed to the particularly shallow depth of the zones relative to the deeper confining layers.

Trees and their root systems were found to have an effect on overall levee stability. Results indicated that a tree can increase or decrease the factor of safety with respect to slope stability depending on the location of the tree on the levee. Additionally, when wind speeds greater than 40 MPH are considered, the factor of safety decreases for all tree locations evaluated for this study (top of slope, midslope, and toe of slope). In this study, reductions in factor of safety reflect specific conditions and may not represent the worst case scenario at these sites. Because of the extreme variability in geology, tree species, climate, and soils, the impact of trees on levees must be analyzed on a case-by-case basis. However, this study does reveal that the tree weight, tree location, root system, and wind loads are all significant parameters that must be taken into account when evaluating the effect of a tree on slope stability for a particular site.

There are many other possible effects of woody vegetation on a levee that were not studied in this research. These are equally important in attempting to fully understand the impact of woody vegetation on levee integrity as those selected for the ERDC research. The possibility of dead or decaying root systems providing preferential flow paths for piping to occur is a topic that requires further study. In addition, the seepage analysis is limited to studying the onset of internal erosion through addressing the contributing factors. Additional research is needed outside the ERDC scope of work to fully evaluate the progression of piping. Until advances are made in this area, it is difficult to fully assess the impact of woody vegetation on the progression of piping.

Efforts reported in this research were focused on living, healthy woody vegetation. Results from numerical analyses were based on models from sandy or silty sand levees. Levees consisting of clay were not included in the ERDC numerical analyses. This research did not address performance of levee systems with the presence of dead, woody vegetation and decaying roots. Other areas of concern that lie outside the scope of work are the contribution, if any, of windthrow and animal burrows to seepage; the impact of woody vegetation within a levee channel on the hydraulic conveyance of a river; biological impacts, such as the prevention of growth of protective grass cover beneath a tree; and the contribution of woody vegetation to scour and erosion. The effect of woody vegetation on levee inspection, maintenance, and accessibility to the levee for flood fighting were not considered in this study. To have a more complex understanding of potential impacts of woody vegetation on levees, further research in these areas is needed.

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Preface

This research of the effects of woody vegetation on the structural integrity of levees was sponsored by the U.S. Army Corps of Engineers (USACE), Headquarters.

This investigation was conducted during the period of October 2009 to September 2010. The project manager for the study was Dr. Maureen K. Corcoran, Geotechnical and Structures Laboratory (GSL). Dr. John F. Peters (GSL) provided the technical oversight. The principal investigators for the research are Dr. Joseph B. Dunbar (GSL), M. Eileen Glynn (GSL), Dr. Christopher Kees (Coastal Hydraulics Laboratory), Jose L. Llopis (GSL), S. Kyle McKay (Environmental Laboratory (EL)), Dr. J. Craig Fischenich (EL), Dr. Janet E. Simms (GSL), Dr. Fred T. Tracy (Information Technology Laboratory), and Dr. Johannes Wibowo (GSL).

The research direction was provided by Dr. Michael K. Sharp, ERDC Technical Director for Water Resources Infrastructure (WRI) and Dr. Maureen K. Corcoran, Assistant Technical Director for WRI. COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

This volume is the fourth of four research volumes documenting initial research conducted by the U.S. Army Engineer Research and Development Center (ERDC) on the effects of woody vegetation on levees. The fifth volume includes a description of the agency technical review (ATR) process and the comments from the review. The research includes data collected and analyzed during this study, as well as those data previously collected by state and federal agencies and their contractors. Major components of this project included site selection, characterization, and analysis (including levee location, geometry, and geology of soils within and underlying the levee); field studies (including tree properties and identification), and estimation of root ball dimensions using electrical resistivity, electromagnetic, and ground-penetrating radar, as well as root excavation); and numerical simulation modeling (including sensitivity and deformation analysis).

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	2.54	centimeters
inches	0.0254	meters
Miles	1.61	kilometers
miles (U.S. statute)	1,609.347	meters

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1 Introduction

At the request of Headquarters, USACE (HQUSACE), in July 2007, the U.S. Army Engineer Research and Development Center (ERDC) conducted an extensive literature review focusing on the effects of woody vegetation on earthen levee performance. The review revealed that minimal scientific data exist on the scientific relationship between structural performance of levees and woody vegetation. Because of the lack of data, HQUSACE concluded that further research was needed to provide input into future guidance. In April 2008, HQUSACE requested that ERDC conduct research on this issue. ERDC formed a team consisting of scientists and engineers with geotechnical, environmental, geological, biological, and geophysical expertise to assess the impact of woody vegetation on levee performance of earthen levees using scientific and engineering methods.

Because of variability in methods used and the magnitude of data collected for the ERDC research, it is often cumbersome for the reader to understand exactly what was accomplished and how the data were used. To better understand the data reported and discussed in the previous three volumes, questions to summarize this research are listed in the following sentences.

The questions pertinent to this study are:

1. What techniques are successful in identifying the spatial extent of root systems in situ?
2. Are field methods successful in identifying in situ soil properties that may be affected by a root system and hence, affect levee performance?
3. What are the parameters revealed in the numerical models that may be sensitive to the presence of a root system?
4. What variables are the most critical to the structural performance of the levee and the tree location and specific conditions (e.g., flood height and duration) that would most likely pose problems?
5. The underlying question is, “Does woody vegetation affect the levee structure?”

Concise answers to these questions are discussed in Chapter 5 of this volume.

2 Project Scope of Work

Research of woody vegetation on levees by ERDC involved the study of two levee failure mechanisms: internal erosion and cases of simple, deep-seated slope stability. These particular topics were selected based on input from federal and state agencies, which showed that directing the research toward these two mechanisms would advance the understanding of the interaction of roots within an engineered levee. The possible influence of living, woody vegetation on these prevalent failure mechanisms are obviously linked with levee performance, and the investigation to support research on these potential failures provides valuable insight into the interaction of the soil matrix and a root system. The selection of slope stability and seepage for this research does not diminish the need for future research on other topics related to the effects of woody vegetation on levees. Rather, this study should be viewed as an initial research effort into a very complex issue.

This study consists of the following three interrelated components:

1. Site visits, field data collection, and laboratory testing to obtain pertinent information necessary to support subsequent modeling and simulation efforts.
2. Modeling and simulation of the engineering, geological, and environmental conditions, and structural performance of the levee system, relative to the initiation of internal erosion and slope stability under various loading conditions.
3. Developing results and conclusions regarding engineering impacts of woody vegetation on levee performance.

The analytical research focused on sand and silty levees, and applicability of some of the engineering conclusions with regard to levees with less permeable material (i.e., clay) might require additional computations. This research did not address the performance of a levee system with the presence of dead woody vegetation and decaying roots. Other areas of concern that lie outside the scope are the influence of windthrow and animal burrows on seepage; impact of woody vegetation within a levee channel on the hydraulic conveyance of a river; and the role of woody vegetation in scour and erosion. The effect of woody vegetation on levee inspection, and maintenance, and accessibility to the levee for flood fighting were not considered in this study. The exclusion of these topics is not intended to diminish their importance in future research.

This ERDC study included extensive descriptive site studies that were essential to this initial research. Field sites are divided into two categories, site characterization and site assessment, depending on the level of both field data collection and numerical analyses. Site characterization consisted of conducting quantitative field tests (e.g., soil type, soil properties, root characterization, and root pullout tests) to characterize both tree roots and soil. Site assessment were limited field investigations used to gather qualitative information on site conditions and root systems. Sites and type of data gathered and analyzed at each site are listed in Table 1.

Table 1. Data gathered and analyses conducted for each site studied in the ERDC research.

	Seepage	Slope Stability	Geophysics	Hydraulic Conductivity	Root Characterization	Root Pullout	In Situ Soil Parameters	Field Observation
Site Characterizations								
Sacramento, CA	•	•	•	•	•		•	•
Burlington, WA	•	•	•	•	•	•	•	•
Albuquerque, NM	•	•	•	•	•	•	•	•
Portland, OR	•		•	•		•	•	•
Site Assessments								
New Orleans, LA			•		•			•
Boca Raton, FL				•			•	•
Lewisville, TX			•					
Danville, PA				•			•	•
Vicksburg, MS			•	•	•		•	•
Lake Providence, LA								•

3 Analysis Criteria

The objectives of the study were to evaluate the influence of internal erosion and slope stability of living woody vegetation on levee performance by using standard engineering analysis techniques. Reliance on standard engineering methods provide a link to precedence based on past levee performance while also providing objective measures that can be used for comparison.

Standard engineering analysis techniques used by the ERDC research consisted of seepage analyses using the finite element method in both two-dimensional (2-D) and three-dimensional (3-D) settings and stability analysis using limit equilibrium methods for 2-D analyses and deformational analyses in three dimensions. The study was primarily performed using 2-D cross-sectional analyses, with 3-D analyses restricted to fewer cases than those used in the 2-D analyses. Pore pressure and phreatic surface from the seepage analysis were used in the slope stability numerical model to determine effective stresses for strength computations. Root dimensions collected at Sacramento, CA, were used for all the 2-D models.

This issue entails two questions. First, how might woody vegetation create conditions that would initiate internal erosion? Second, once initiated, will propagation of erosion occur? The first question was addressed by extensive parametric analyses in the ERDC research. The results of the parametric study were put into perspective by comparing hydraulic conductivity values to values measured in the field

Seepage analyses were conducted assuming both transient and steady-state conditions. A common approach to levee design is to assume steady-state conditions under flood stage. This assumption is reasonable for design purposes but is generally more conservative than a transient solution. In this study, transient solutions were also considered. This study may at some point be incorporated into a probability-based method based on event trees, whereby possible durations of the flood become events with associated probabilities. Independently analyzing the effects of woody vegetation on slope stability and the initiation of internal erosion reduces the larger problem to a set of more manageable sub-problems. However, the probability of failure of events, such as internal erosion and piping, are still difficult to determine. This is why the use of numerical modeling to compute the flow field is important. This computation of variables of the flow field, such as exit gradient and pore pressure (commonly used in levee design), produces tangible data to use in applying engineering best practices to determine these probabilities. However, a concern in using the flow field from the numerical models as an indicator of the effects of woody vegetation on certain aspects of levee performance, such as slope stability and internal erosion, is that assumptions inherent in numerical models might not adequately represent the real world in every analysis. In the ERDC research, numerical models were used to compute pore pressures and exit gradients that represent the flow field. These variables were used to approximate the initiation of internal erosion.

The variations in material properties generally affect the flow field only locally. This lack of influence of far-removed variation is a mathematical property of the equations that govern steady-state seepage flow. Failure by piping and erosion of soil particles stem from progressive mechanisms that emanates from local conditions. The critical issue is to understand the extent to which woody vegetation increases the risk that failure occurs by these progressive mechanisms.

More importantly, analyses revealed variables that were the most critical to structural performance of the levee, and the particular combination of tree location and specific conditions (e.g., flood height and duration) that are most likely to pose problems. General trends noted from these analyses contributed to the final conclusions reached by this research.

The choice of levee systems studied was based on USACE districts and divisions and state and local support provided to the ERDC study team. The levee composition was discovered after the levee and engineering data were obtained. Generally, the western states are where most of the vegetation issues occur. These are areas that experience low rainfall, are near steep mountainous terrain, where mechanical weathering generally dominates (as opposed to chemical weathering), and where pervious (sandy) floodplain soils are generally present. Materials used to build the levee are dredged or floodplain soils that were scraped from or adjacent to the channel. Clay levees were not studied in detail because the focus was on western states with the majority of vegetation-related issues. Clay levees are mainly confined to central and eastern states, in meandering floodplains (i.e., have a well defined top blanket or stratum) or occur in the delta parts of the river systems floodplain. Geography and construction play a major role in selecting soils for levee construction.

4 Project Scope of Work

The ERDC research approach was structured from scientific and engineering data gaps found after an extensive literature review was completed. Data gaps include overall lack of scientific research involving the influence of a root system on an engineered levee. The purpose of this research was to develop an understanding of the impact of woody vegetation on the initiation of internal erosion and on slope stability of earthen levees using scientific and engineering methods.

The procedure used in the ERDC research is based on the following tasks. For more detailed description of these steps, refer to the volume or publication associated with each topic.

- Task 1 – Conduct an extensive literature review (Corcoran et al. 2011)
- Task 2 – Select study sites (Volume I)
- Task 3 – Collect field data (Volume II)
- Task 4 – Numerical model simulation (Volume III)
- Task 5 – Develop conclusions (Volume IV)

These volumes include data collected and analyzed during this study, as well as those data previously collected by state and federal agencies and their contractors.

5 Results and Conclusions

There is caution in interpreting results from what is considered as initial research into a complex topic. Results of this study are restricted to specific locations on certain levees and cannot be perceived as a blanket assessment of an entire levee system even within the studied levee.

The following questions are designed to concisely summarize the ERDC research.

What techniques are successful in identifying the spatial extent of root systems in situ?

The purpose of this question is to discuss techniques that are effective in mapping a root system for research on the effects of woody vegetation on levee performance. Efficacy was measured as the estimation of bulk properties of the root system (e.g., extent, volume) as well as detection of individual roots. Invasive methods were used in the ERDC study to calibrate noninvasive and hence, non-destructive methods, but an end result to future research should be to reduce the need for invasive methods. Table 2 summarizes conditions under which various geophysical techniques were evaluated.

Electrical resistivity imaging (ERI) measurements proved useful, relative to other geophysical method, such as ground penetrating radar (GPR), or electromagnetic (EM) techniques, in determining the size and extent of tree root balls. Conversely, in favorable soil conditions, GPR was shown to be relatively effective in predicting location and orientation of individual roots. The use of both ERI and GPR techniques should be locally validated with manual excavation. The excavation does not include removing soil around the entire root system but rather exposing the roots by removing blocks of soil to validate geophysical interpretation.

Table 2. Conditions under which various geophysical techniques were evaluated for estimating the spatial extent of tree roots.

Location	Site Description[a]	Geophysical Survey Results Summary			
Sacramento, CA 38°29′20″ N 121°33′05″ W	A reach of sandy levee in urban Sacramento on the east bank of the Sacramento River. The tree used in the field investigation was located midslope on the landside of the levee. <u>Soil</u> Sand on top of silty clay (contains a 3 ft (0.9 m) clay-mixed with sand) <u>Levee geometry</u> Height: 18 ft (5.5 m) Crown Width: 20 ft (6.1 m) Toe-Toe Width: 155 ft (47.2 m) Soil: silty sand <u>Tree species/Dimensions</u> Valley oak (*Quercus lobata* Née) DBH[c]: 29.5 in. (75 cm) Drip line: 55.1 ft (16.8 m) Height: 49.2 ft (15 m) <u>Climate</u> Mean annual temperature: 61.1°F (16.2°C) Mean annual rainfall: 1.8 in. (4.5 cm) Prevailing winds are from the south		Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		ERI (avg)	1.6	1.5	1.6
		GPR	1.4	1.7	0.35
		GPR: individual roots probably detected but subsurface clutter makes it difficult to identify them.			
		EM	No correlation with tree root zone		
		SME	Average Moisture[d] (%)	Average Root Volume Ratio (= root vol/cell vol)	
			8.92	0.02547	
Albuquerque, NM 35°08′33.35″ N 106°40′34.54″ W	**Site 1** – A reach of sandy levee in urban Albuquerque on the east bank of the Rio Grande River south of Montano Blvd. The tree used in the field investigation was located on the waterside of the levee approximately 49.2 ft (15 m) from the levee toe. <u>Soil</u> Sand (with a toe drain with gravel filter and sand) on top of an aquifer sand	**Site 1**	Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		ERI	No correlation with tree root zone		
		SME	Average Moisture[d] (%)	Average Root Volume Ratio (= root vol/cell vol)	

Location	Site Description[a]	Geophysical Survey Results Summary			
	<u>Levee geometry</u> Height: 18 ft (5.5 m) Crown Width: 20 ft (6.1 m) Toe-Toe Width: 55 ft (16.8 m) Soil: sand (poorly graded) <u>Tree species/Dimensions</u> Fremont cottonwood (*Populus fremontii*) DBH[c]: 16.1 in. (41 cm) Drip line: 35.1 ft (10.7 m) Height: 36.1 ft (11 m)		7.91	0.03814	
35°09′55.23″ N 106°40′01.21″ W	Site 2 – A reach of sandy levee in urban Albuquerque on the west bank of the Rio Grande River north of Montano Blvd. The trees used in the field investigation were located on the waterside of the levee approximately 32.8 ft (10 m) from the levee toe. <u>Tree species/Dimensions</u> 2 Fremont cottonwoods (*Populus fremontii)* DBH[c]: 16.1 in. (58 cm) Drip line: 45.9 ft (14 m) Height: 39.3 ft (12 m) DBH[c]: 10.6 in. (27 cm) Drip line: 30.2 ft (9.2 m) Height: 29.5 ft (9 m) <u>Climate</u> Mean annual temperature: 56.8°F (13.8°C) Mean annual rainfall : 8.9 in. (22.6 cm) Prevailing winds are from the north	Site 2	Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		ERI	No correlation with tree root zone		
		SME	Average Moisture[d] (%)	Average Root Volume Ratio (= root vol/cell vol)	
			13.17	0.07782	

Location	Site Description[a]	Geophysical Survey Results Summary			
Burlington, WA 48°27′47″ N 122°18′47″ W	Sample tree was 16.4 ft (5 m) from the levee toe on the waterside of the west bank of the Skagit River levee system. <u>Levee geometry</u> Height: 10 ft (3.0 m) Crown Width: 20 ft (6.1 m) Toe-Toe Width: 115 ft (35.0 m) Soil: silty sand <u>Tree species/Dimensions</u> Western red cedar (*Thuja plicata)* DBH[c]: 56.2 in. (143 cm) Drip line: 40.0 ft (12.2 m) Height: 65.6 ft (20 m) Mean annual temperature: 50.9°F (10.5°C) Mean annual rainfall: 32.7 in. (83.1 cm) Prevailing winds are from the south-southeast		Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		ERI (avg)	10	10	1.5 -2
		GPR	12	12	0.62
		GPR: Individual roots detected			
		EM	10	10	----
		SME	Average Moisture[d] (%)	Average Root Volume Ratio (= root vol/cell vol)	
			15.18	0.05117	
Vicksburg, MS 32°12′41″ N 90°48′21″ W	**Site 1** - Test site was in a rural pasture approximately 8.7 mi (14 km) south of Vicksburg. Sample tree was on an embankment sloping gently from SW to NE at approximately 5 deg. <u>Levee geometry</u> No levee <u>Soil</u> Windblown silt (ML) <u>Tree species/Dimensions</u> Southern red oak (*Quercus falcate*) DBH[c]: 11.4 in. (29 cm) Drip line: 24.6 ft (7.5 m) Height: 24.6 ft (7.5 m)		Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		ERI	3.6	1.8	1.0
		GPR	4.5	3.5	----
		SME	Average Moisture[d] (%)	Average Root Volume Ratio (= root vol/cell vol)	
			----	----	

Location	Site Description[a]	Geophysical Survey Results Summary			
32°12′31.97″ N 90°48′3.27″ W	**Site 2** – <u>Levee geometry</u> No levee <u>Tree species/Dimensions</u> Loblolly pine (*Pinus taeda*) <u>Soil</u> Gravelly sand (GW-SP) <u>Climate</u> Mean annual temperature: 65.5°F (18.6°C) Mean annual rainfall: 58.0 in. (147.3 cm) Prevailing winds are from the south		No geophysical surveys		
New Orleans, LA 30°00′41.17″ N 90°01′52.63″ W	**Site 1** - IHNC Site – A reach of clay levee on the Inner Harbor Navigation Canal in an urban environment. The tree used in the field investigation had been cut several days prior to the field study. The tree was located on the toe of the levee. The survey was conducted only on the levee side of the tree. <u>Levee geometry</u> I-Wall Height: 12.5 ft (3.8 m) Slopes: 1V (vertical):2.5H (height) Crest: 10 ft (3.05 m) Toe-Toe Width: 60 ft (18.3 m) <u>Soil</u> Clay (CL-CH) <u>Tree species/Dimensions</u> Hackberry (*Celtis occidentalis)* DBH[c]: 25.2 in. (64 cm)	Site 1	Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		GPR	1	1.8	----
		GPR: Individual roots not detected.			
		EM	No correlation with tree root zone		

<table>
<tr><th>Location</th><th>Site Description[a]</th><th colspan="4">Geophysical Survey Results Summary</th></tr>
<tr><td rowspan="4">29°59′15.33″ N
90°07′29.71″ W</td><td rowspan="4">Site 2 - 17th Street Site – A reach of clay levee on the 17th Street Canal. Two oak tree stumps that had been cut approximately 2 years prior to the study were located midslope of the levee. The survey was conducted only on the levee side of the tree.

<u>Levee geometry</u>
I-Wall
Height: 13.5 ft (4.1 m)
Slopes: 1V:2.5H
Crest: 10 ft (3.04 m)
Toe-Toe Width: 60 ft (18.3 m)

<u>Soil</u>
Clay (CL-CH)

<u>Tree species/Dimensions</u>
Oak trees (unknown species)
DBH[c]: 43.3 in. (110 cm) and 35.4 in. (90 cm)

<u>Climate</u>
Mean annual temperature: 68.5°F (20.3°C)
Mean annual rainfall: 61.9 in. (157.2 cm)
Prevailing winds are from the south</td><td>Site 2</td><td colspan="3">Mapped lateral influence of tree root zone with respect to levee axis</td></tr>
<tr><td>Method</td><td>Parallel (m)</td><td>Perpendicular (m)</td><td>Depth (m)</td></tr>
<tr><td>GPR</td><td>----</td><td>----</td><td>----</td></tr>
<tr><td>EM</td><td colspan="3">No correlation with tree root zone</td></tr>
<tr><td rowspan="5">Portland, OR
45°33′32″ N
122°26′14″ W</td><td rowspan="5">Test site is located approximately mid-slope on the protected slope of a sandy levee. Eight trees, roughly in a 150-ft (45.7 m) long line and parallel to the crest of the levee, were used in the field study.

<u>Levee geometry</u></td><td></td><td colspan="3">Mapped lateral influence of tree root zone with respect to levee axis</td></tr>
<tr><td>Method</td><td>Parallel (m)</td><td>Perpendicular (m)</td><td>Depth (m)</td></tr>
<tr><td>ERI</td><td colspan="3">No correlation with tree root zone</td></tr>
<tr><td>GPR</td><td>NA</td><td>6.0</td><td>0.5</td></tr>
<tr><td colspan="4">GPR: Individual roots detected.</td></tr>
</table>

Location	Site Description[a]	Geophysical Survey Results Summary			
	<u>Soil</u> Sandy soils; levee fill-silty sand; levee foundation-silty clay <u>Tree species/Dimensions</u> 8 Fremont cottonwoods (*Populus fremontii)* DBH[c]: range ~19.7-39.4 in. (50-100 cm) Drip line: Overlapping drip lines Height: ~49.2-32.8 ft (10-15 m) <u>Climate</u> Mean annual temperature: 53.4°F (11.9°C) Mean annual rainfall: 44.3 in. (112.6 cm) Prevailing winds in summer are from the NNW and from the ESE in the winter.	EM	No correlation with tree root zone		
Lewisville, TX 33°03′51″ N 96°59′15″ W	The studied tree is located on the toe of the western end of Lewisville Dam. <u>Soil</u> Clay <u>Tree species/Dimensions</u> Post oak (*Quercus stellata)* DBH[c]: 43.3 in. (110 cm) Drip line: 15 m (49.2 ft) Height: 10 m (32.8 ft) <u>Soil</u> Clay (fat) <u>Climate</u> Mean annual temperature: 64.0°F (17.8°C) Mean annual rainfall: 34.1 in. (86.6 cm) Prevailing winds are from the south.		Mapped lateral influence of tree root zone with respect to levee axis		
		Method	Parallel (m)	Perpendicular (m)	Depth (m)
		ERI	3.5	2.7	1.5
		EM	No correlation with tree root zone		

Location	Site Description[a]	Geophysical Survey Results Summary
Danville, PA 40°57′49.45″ N 76°37′38.72″ W 40°57′18.86″ N 76°36′51.99″ W	**Site 1** – north end of Danville levee system on the Susqueanna River; levees composed of very dense silty sand **Site 2** – south end of Danville levee system on the Susquenanna River; levees composed of very dense silty sand Mean annual temperature: Not available Mean annual rainfall: 43.8 in. (111.3 cm) Prevailing winds are generally from the west, but more northerly in the winter and more southerly in the summer.	No geophysical surveys
Lake Providence, LA 32°48′26.48″ N 91°10′31.53″ W	Edge of oxbow lake of the Mississippi River adjacent to Hwy 65. Active sand boils on lake; approximately 0.5 mi from active sand boils adjacent to the Mississippi River levee <u>Tree species/Dimensions</u> Cypress (*Taxodium distichum*) <u>Climate</u> Mean annual temperature: 64.0°F (17.8°C) Mean annual rainfall: 63.47 in. (161.2 cm)	No geophysical surveys.

[a] Temperature and precipitation values are average annual from the weather station closest to the site. (USDC 2010). Prevailing wind data are from WRCC (2010).

[b] GPR – ground-penetrating radar, ERI – electrical resistivity imaging, EM – electromagnetic, SME – sub-sampled manual excavation.

[c] DBH – diameter at breast height.

[d] Gravimetric moisture content.

The two geophysical methods best suited for detecting and delineating roots and root zones are electrical resistivity imaging (ERI) and ground penetrating radar (GPR). ERI is better suited for measuring the minimum extent of a tree's root zone whereas GPR can be used to map shallow roots. ERI generally performed better at sites where soils are more electrically conductive (such as the clays found in Lewisville and Vicksburg). ERI did not perform as well in less electrically conductive coarse-grained soils found in Albuquerque and Portland. GPR is best for resolving the depth and location of individual tree roots. This method performs best in electrically resistive soil such as moist sand. Electrically conductive wet clay severely limits the depth of investigation for GPR. This finding indicates that root detection with geophysical techniques should be applied only in typically suitable instrument conditions.

The trees studied at Lewisville and Vicksburg were oaks, which have a spatially dense root system whereas the trees studied at Albuquerque and Portland were cottonwoods with more expansive running roots but a less dense root ball. It is possible that the oaks' denser root zones might be providing a greater contrast in electrical conductivity between it and the background soil than the cottonwoods' less dense root zone and background soil, thus making oak root zones easier to detect. Moreover, the material density of cottonwood roots was less than that of the oaks, and may have exacerbated this effect. Thus, the ability to map a root zone may be as much a function of tree species as soil type. More field testing would be needed to isolate this synergistic effect.

A high degree of subsurface heterogeneity, large topographical gradients, and very dry surface soils can influence the quality of geophysical reading and affect interpretation results. A limitation of the ERI method is that the measured reading at a given point is a weighted average of the effects over a large volume of material. This causes the detection or resolution of smaller targets to become more difficult as a function of depth. The distribution of resistivity readings on the ground surface can be accurately modeled given the number of layers, layer thicknesses, and layer resistivity values (forward modeling). However, the ERI inversion process (the process by which the distribution of subsurface resistivity values are determined) does not provide a unique interpretation. If more information is known about subsurface conditions (i.e., number of layers, layer thicknesses), the inversion results have higher confidence. High contact resistance problems occur when the near surface soils are so resistive (usually caused by extremely dry surface soil) that the current electrode has difficulty injecting current into the ground. In this case, saltwater is usually poured around the base of the electrodes to lower the electrode-soil contact resistance. Other factors that affect electrical resistivity surveys are the presence of metallic fences, rails, pipes, or other soil-contacting conductors that could provide a short circuit path. In Sacramento, GPR results were limited by subsurface heterogeneity, which induced variability in the signal. The inability to attribute signal changes to roots, subsurface debris, changes in soil moisture, or other anomalies reduce the efficacy of the tool at this otherwise suitable location.

These factors highlight the need for additional prior information about subsurface conditions, whether from borings, other geophysical explorations methods, or invasive sampling. Considering the current state of knowledge, it is advisable to accompany all geophysical investigations with sub-sampled excavations to verify results. An unexamined alternative in future sampling would be to collect geophysical data at nearby sites with and without trees to examine a relative change in signal propagation (as was conducted with permeability tests).

Are field methods successful in identifying in situ soil properties that may be affected by a root system, and hence affect levee performance?

The purpose of the in situ hydraulic conductivity tests was to provide unbiased comparative data to determine if root growth alters hydraulic conductivity within a soil horizon. To accomplish this objective, hydraulic conductivity of the soil/root matrix was measured in situ within and around the root mass of a tree and compared to hydraulic conductivity measured around a control site without tree roots within the same reach of levee. Field samples for hydraulic conductivity around a tree did not always correspond to the tree root zone used in the 2-D seepage model discussed in Volume II.

Graphs (Figures 1 and 2) display the difference in means of log-transformed data for both a tree site and non-tree control site. Error bars represent 95% confidence intervals for difference in the means. If the confidence interval lies entirely above the zero reference line, then log tree mean is statistically significantly greater than log control mean and vice versa if the confidence interval lies entirely below the zero line. Confidence intervals that included zero indicated that the difference in means is not statistically significant.

Results of statistical comparisons between the mean hydraulic conductivities of the tree data and control data were inconsistent for the shallow soil horizon. No significant differences between tree and control data were found at the deeper soil horizon. Because of this discrepancy, a numerical model was used for a parametric analysis of hydraulic conductivity to test the sensitivity of this parameter to a flowfield. It was not determined why shallow soil horizon data for some of the control areas were higher than the respective tree data and some were lower, but it may be linked to soil parameters, such as type, texture, or structure. Thus, these analyses by themselves are not conclusive. One must consider other factors that affect hydraulic conductivity such as: if the testing apparatus was appropriate for the property being measured, if the scale of the test was appropriate, and were enough data points collected to evaluate the variability of the data. At the time of field testing, the test and analysis plan, scale of measurement and test apparatus were assumed appropriate. In future research, the following are recommended: testing locations be added per tree; testing be conducted closer to the tree trunk; larger scale tests (infiltration tests) be added to the investigation; and study design include more rigorous control of tree species, soil type, and ambient conditions (climate and season).

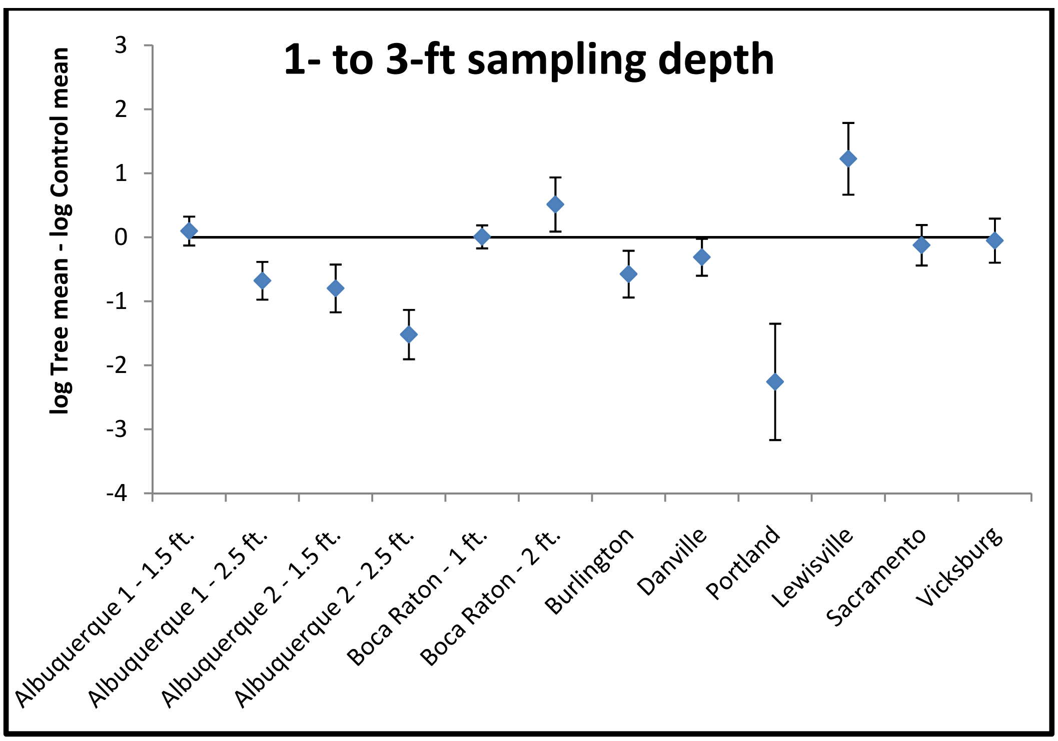

Figure 1. Difference between mean hydraulic conductivities for shallow depth (1 to 3 ft) for both the tree and control sites with 95% confidence interval.

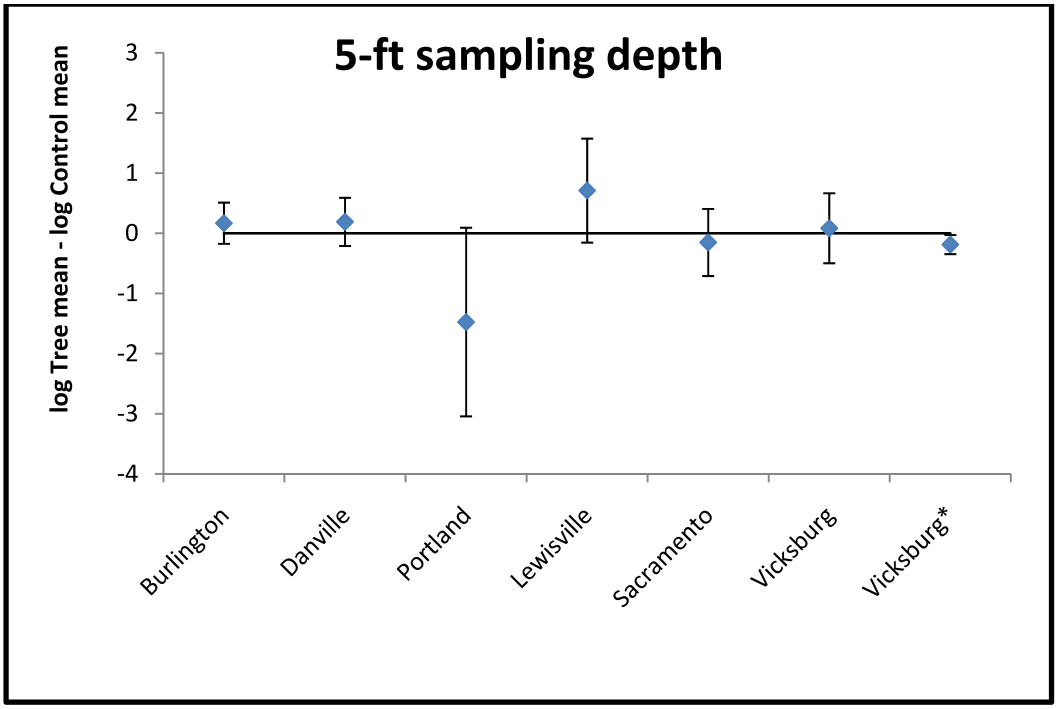

Figure 2. Chart showing difference between tree and control mean hydraulic conductivities and the 95% confidence intervals for tests conducted at 5 ft. Vicksburg is shown with and without the outlier included in the data set. The Vicksburg data without the outlier (Vicksburg *) shows a smaller confidence interval.

What are the parameters revealed in the numerical models that may be sensitive to the presence of a root system?

The sensitivity analyses from the SEEP2D model results provided an assessment of the hypothetical impact of woody vegetation on levees with respect to seepage flow for various tree positions and levee cross sections. These analyses were divided into three approaches. First, the volume around a root zone was assigned various values of β with conditions within the zone assumed uniform. This first approach established the basic observation that root zones generally affected the flow field within their immediate vicinity but have virtually no influence on the overall flow field.

After discussions with USACE district engineers, the importance of variability within the root zone was investigated to determine the potential for root-induced flaws to initiate failure. In the second approach, the possibility of a defect focusing flow in a localized channel was investigated by imposing various patterns of heterogeneity within the root zone. Both 2-D and 3-D cases were considered. The analyses of this second approach revealed a great deal about the potential for defects to initiate failure.

The third approach was strictly a 3-D analysis using real root geometries, in which patterns of contrasting hydraulic conductivity were deposited to form the shape of the root mass. In extreme cases, roots could either represent zones of virtually no hydraulic conductivity or zones of high hydraulic conductivity caused by loose soil surrounding each root or channels produced from living roots. It is emphasized that all of the cases studied in all three approaches were hypothetical whose significance must be weighed against field measurements.

Two general trends became apparent from the sensitivity analysis. First, the most critical location of the tree along the slope of the levee, in terms of detrimental impact on slope stability, was at the top of the levee. Placement of trees at midslope or at the toe of the levee had little to no impact on the slope stability. The major impact of the tree was its loading caused by its weight. Root strengthening of the soil had little impact on the factor of safety for deep-seated sliding. Therefore, root strength was not a critical parameter. Second, hydraulic conductivity had little to no impact on the seepage flow paths or gradient of the levee system. The most likely impact on the flow path or critical gradient occurred when the tree was located at the toe of the levee, but this impact depended on the degree to which the tree altered hydraulic conductivity of the soil. Results from this limited analysis also support an assumption by USACE field personnel that changes in hydraulic conductivity on the riverside do not affect the landside flow conditions.

What variables are the most critical to the structural performance of the levee, and at what locations on the levee is woody vegetation most likely to pose problems?

Results from the SEEP2D models using the first approach in the seepage analyses showed that trees located on the slopes above the phreatic surface had a limited effect on the seepage, the greatest effect being felt from trees at the landside levee toe. For these studies, a rectangular block of varying hydraulic conductivity was used to model an inferred root zone. Nodes within the zone and also outside the zone were selected for tabulating the magnitude of gradient and pore pressure. The study was based on the implication that tree roots alter soil permeability. In the model, a woody vegetation zone is defined as the portion of the mesh where the hydraulic conductivity (k) for this zone is modified by the multiplier β in Equation 1:

$$k_{veg} = \beta k_{no-veg} \tag{1}$$

where:

$k_{no\text{-}veg}$ = hydraulic conductivity of the zone without woody vegetation
k_{veg} = hydraulic conductivity of the zone with woody vegetation
β = a parameter set to various values (e.g., 0.001, 0.01, 0.1, 0.5, 1, 2, 10, 100)

Increasing the hydraulic conductivity implies that the soil in the woody vegetation zone is more pervious due to the soil being unconsolidated or preferred paths being developed in the root system. Conversely, decreasing the hydraulic conductivity means that the roots are an impediment to flow, and thus the soil is less pervious than without the roots. A variety of conditions were modeled that reflect both the waterside and landside conditions. Critical locations are different depending on the circumstances (i.e., geology, levee geometry, blanket thickness, mode of failure) at each site. The critical condition of a zone at the landside toe with a thin blanket and high water conditions were not stated, but the impact of the zone along the levee profile were evaluated for any impact to the critical location.

Based on these analyses, it is significant that only trees just beyond the toe of the levee or at the bottom of the de-watered drainage ditch made any appreciable difference to the value of the exit gradient for the cross sections considered in this study. The case where the root system causes a reduction in hydraulic conductivity by more than a factor of 10 shows an increase in hydraulic gradient as a result of low hydraulic conductivity of the root zone blocking the flow of water.

In Table 3, tree positions that can be a potential problem for levee stability are highlighted in red. A dash is given when the phreatic surface is below the given significant point. Results are from both steady-state and transient (highlighted in yellow) solutions.

Changes in pore pressure caused by differences in hydraulic conductivity of less than an order of magnitude are small, especially if 3-D geometries are considered. In general, the effect of a single tree in three-dimensional flow on levee performance is smaller than in a two-dimensional flow field. Results from the 2-D analyses provided a representation of pore pressure conditions, a finding that was particularly important to the reliability of the slope stability assessment.

Gradients are lower in and near root systems with root zones having hydraulic conductivities more than 10 times greater than that of the surrounding soil, thus decreasing the concern for exceeding the critical gradient. Note however, in this case, seepage velocity is increased, which is a contributing factor to soil erosion.

Table 3. Exit gradients at nodes for woody vegetation zones in the approach evaluating changes in hydraulic conductivity for each levee site using different values of β.

	$\beta = 0.01$	$\beta = 1$	$\beta = 100$
Sacramento, CA, with river at EL 29 ft – Exit gradient calculated at levee toe			
Zone beyond the toe	0.49	0.33	0.01
Zone on the toe	0.24	0.33	0.03
Zone midway on the steeper landside slope	0.33	0.33	0.33
Zone near the top of the landside	0.33	0.33	0.33
Zone at the river height on the riverside	0.33	0.33	0.33
Zone at the change in slope on the riverside	0.33	0.33	0.33
Zone near the end of the levee sand on the riverside	0.33	0.33	0.33
Sacramento, CA, with river at El. 29 ft – Extended Woody Vegetation Zone Vertically – Exit gradient calculated at levee toe			
Zone beyond the toe	0.52	0.33	0.01
Sacramento, CA, with river at El. 29 ft – Extended Woody Vegetation Zone Horizontally – Exit gradient calculated at levee toe			
Zone beyond the toe	1.48	0.33	0.01
Sacramento, CA, with river at El. 29 ft – Degradation of Slurry Wall – Exit gradient calculated at levee toe			
Zone beyond the toe	0.33	0.33	0.33
	$\beta = 0.01$	$\beta = 1$	$\beta = 100$
Sacramento, CA, with river at El. 26 ft – Exit gradient calculated at levee toe			
Zone beyond the toe	0.43	0.28	0.00
Zone beyond the toe – Transient	-	-	-
Zone on the toe	0.19	0.28	0.02
Zone midway on the steeper landside slope	0.28	0.28	0.28
Zone near the top of the landside	0.28	0.28	0.28
Zone at the river height on the riverside	0.28	0.28	0.28
Zone at the change in slope on the riverside	0.28	0.28	0.28

Table 4. Exit gradients at nodes for woody vegetation zones in the approach evaluating changes in hydraulic conductivity for each levee site using different values of β.

	β = 0.01	β = 1	β = 100
Zone near the end of the levee sand on the riverside	0.28	0.28	0.28
Burlington, WA, first cross section – Exit gradient calculated at levee toe			
Zone beyond the toe	1.09	0.81	0.11
Zone beyond the toe – Transient	0.99	0.74	0.11
Zone on the toe	0.59	0.81	0.22
Zone nearly halfway to the top of the levee on the landside	0.81	0.81	0.81
Zone nearly halfway to the top of the levee on the riverside	0.80	0.81	0.82
Zone near the heel on the river side	0.80	0.81	0.87
Burlington, WA, second cross section – Exit gradient calculated at levee toe			
Zone on the toe	0.11	0.18	0.01
Zone on the lower slope of the levee on the riverside	0.19	0.18	0.18
Burlington, WA, third cross section – Exit gradient calculated at levee toe			
Zone just beyond the toe	0.92	0.46	0.02
Portland, OR - Exit gradient calculated at lower levee toe			
Zone beyond the lower toe	0.84	0.69	0.11
Zone beyond the lower toe – Transient	0.64	0.53	0.13
Zone just beyond the upper toe of the levee	0.68	0.69	0.69
Zone nearly halfway to the top of the levee on the riverside	0.69	0.69	0.69
Zone at the river elevation on the river side	0.68	0.69	0.69
Albuquerque, NM, with river at El. 4,992 ft – Exit gradient calculated at bottom of de-watered drainage ditch			
Zone near the toe	1.00	0.99	0.99
Zone at the bottom of the ditch	1.11	0.99	0.16
Albuquerque, NM, with river at El. 4,989 ft – Exit gradient calculated at bottom of de-watered drainage ditch			
Zone near the toe	0.86	0.86	0.86
Zone at the bottom of the ditch	0.98	0.86	0.63
Zone at the bottom of the ditch – Transient	0.85	0.74	0.12

In the third approach for the seepage analysis, a defect representing a vertical, single root was modeled based on Schaefer et al. (2010).

The details of the seepage analyses are provided in Tables 5 through 7. At variance to the results of the seepage analysis, trees located on all parts of the slope affected the factor of safety in the slope stability analysis, regardless of proximity of the roots to the phreatic surface. Tables 8, 9, and 10 contain a summary of results from the slope stability analysis under steady state conditons. Results for $\beta = 0.01$ are shown because the greatest effect on slope stability occured when the hydraulic conductivity is reduced at the levee toe, which has the effect of increasing the pore pressure. The effect of increasing pore pressure is a reduction in the effective stress that, in turn, reduces passive resistance. The effect of increasing β is a reduction in pore pressure beneath the toe, which increases the factor of safety.

Table 5. Average vertical seepage gradient through the confining layer, factor of safety for this exit gradient, average horizontal seepage gradient in the foundation, and probability of initiation of erosion in the foundation for different blanket thicknesses and slurry wall options for the Pocket Levee.

Parameter		Cross section		
		1	2	3
Variations in levee geometry	Blanket thickness (T) (ft)	30	5	5
Variations in levee geometry	Slurry wall	Yes	Yes	No
Calculated from SEEP2D	Average vertical seepage gradient	0.29	1.37	1.37
Calculated from SEEP2D	Factor of safety for exit gradient	3.10	0.66	0.66
Calculated from SEEP2D	Horizontal gradient	0.01	0.03	0.03
Interpretation of calculated results based on Schaefer et al. (2010)	Probability of initiation	Negligible	1.0	1.0
Interpretation of calculated results based on Schaefer et al. (2010)	Criterion for probability estimate	T > 25 ft FS > 1.3	FS < 1	FS < 1

In general, this study observed that trees on the upper part of the slope decreased the factor of safety because they add weight. Trees near the toe increased the factor of safety because of the reinforcing effects of the roots and the increased counterweight effect of the tree to slope movement. Trees at midslope have lesser effect on the factor of safety because they act as a load, but not a counterweight and the roots are too shallow to reach the failure zone within the midslope region.

Table 6. Average vertical seepage gradient through the confining layer, factor of safety for this exit gradient, average horizontal seepage gradient in the foundation, and probability of initiation of erosion in the foundation for different cross sections of the Burlington Levee.

Parameter		Cross section		
		1	2	3
Variations in levee geometry	Blanket thickness (T) (ft)	4.10	39.0	48.1
Calculated from SEEP2D	Average vertical seepage gradient	0.43	0.06	0.12
	Factor of safety for exit gradient	2.10	15.0	7.5
	Horizontal gradient	0.20	0.01	0.01
Interpretation of calculated results based on IET procedure.	Probability of initiation	Negligible	Negligible	Negligible
	Criterion for probability estimate	FS > 1.3	T > 25 ft FS > 1.3	T > 25 ft FS > 1.3

Table 7. Average vertical seepage gradient through the confining layer, factor of safety for this exit gradient, average horizontal seepage gradient in the foundation, and probability of initiation of erosion in the foundation for the Portland and Albuquerque levees.

Parameter		Levee	
		Portland	Albuquerque
Variations in levee geometry	Blanket thickness (T) (ft)	3.66	6.00
Calculated from SEEP2D	Average vertical seepage gradient	0.43	0.85
	Factor of safety for exit gradient	2.10	1.06
	Horizontal gradient	0.02	0.02
Interpretation of calculated results based on IET procedure.	Probability of initiation	Negligible	Negligible to 0.25
	Criterion for probability estimate	FS > 1.3	Best to worst case

If wind load is considered in the calculation, the factor of safety decreases at a wind speed of 40 mph and greater for all tree positions and assumptions evaluated. The most significant decrease in the factor of safety is for trees positioned on the top of the levee slope. The factor of safety shown in Tables 9 and 10 is calculated using data gathered on a specific cottonwood tree. For trees of other dimensions (i.e., tree height), the calculated factor of safety might be different. Details of the slope stability analysis are in Chapter 3 of Volume III.

The analyses indicated that the strengthening effect of the roots to the deep-seated failure modes that control levee stability is insignificant. For trees at midslope, roots do not reach the potential failure surface. Where strengthening does affect the potential failure surface, the effect is to drive the critical surface below the root zone, with only a modest increase in the factor of safety. Therefore, root strengthening does not appear to be an issue in levee stability.

Table 8. Factor of safety for Sacramento, CA, levee (landside and riverside) with three different tree locations and three different floodwater levels, with and without wind load. Blanket thickness used in this analysis is 30 ft.

Location	Tree Species	Failure Slope	Wind Speed (mph)	Failure Criteria	Water Level (ft)	Factor of Safety: No Tree	Factor of Safety: Tree at Toe	Factor of Safety: Tree at Mid Slope	Factor of Safety: Tree at Top Slope
Sacramento, CA	Valley oak (*Quercus lobata* Née)	Landside	0	1	23 26 29	1.87 1.70 1.54	2.00 1.77 1.65	1.81 1.62 1.47	1.86 1.66 1.51
				2	23 26 29	1.92 1.76 1.60	2.08 1.89 1.72	1.87 1.71 1.56	1.86 1.66 1.52
				3	23 26 29	1.98 1.79 1.56	2.09 1.88 1.66	1.94 1.75 1.55	1.92 1.71 1.51
		Riverside	0	1	23 26 29	2.00 2.05 2.10	2.11 2.15 2.23	2.04 2.07 2.12	2.13 2.17 2.32
				2	23 26 29	2.08 2.13 2.21	2.12 2.20 2.30	2.05 2.10 2.18	2.07 2.10 2.25
				3	23 26 29	2.15 2.24 2.34	2.21 2.30 2.41	2.15 2.22 2.32	2.14 2.21 2.36
		Landside	5 15 25 40 60 75	2	38.7	1.60 1.60 1.60 1.60 1.60 1.60	1.72 1.71 1.67 1.61 1.46 1.31	1.56 1.55 1.53 1.48 1.37 1.26	1.52 1.51 1.49 1.45 0.66 0.42

Table 9. Factor of safety for Burlington, WA, levee (landside and riverside) with three different tree locations and three different floodwater levels, with and without wind load (β = 0.01).

Location	Tree Species	Failure Slope	Wind Speed (mph)	Failure Criteria	Water Level (ft)	Factor of Safety					
						No Tree	Tree at Toe	Tree at Mid Slope	Tree at Top Slope	Tree at Mid Slope (river-side)	Tree at riverside
Burlington, WA	Western red cedar *(Thuja plicata)*	Landside	0	1	32.7	1.16	1.09	1.04	1.19	1.15	1.15
					38.7	1.03	0.99	1.04	1.04	1.03	1.03
					45.0	0.44	0.70	0.76	0.54	0.39	0.42
				2	32.7	1.51	1.46	1.57	1.53	1.51	1.52
					38.7	1.24	1.39	1.41	1.27	1.25	1.25
					45.0	0.80	1.02	0.91	0.83	0.79	0.79
				3	32.7	1.80	1.95	1.98	1.84	1.80	1.80
					38.7	1.50	1.70	1.64	1.55	1.50	1.50
					45.0	1.02	1.20	1.15	1.08	1.03	1.03
		Riverside	0	2	32.7	1.88	1.88	1.88	1.88	1.92	1.88
					38.7	2.14	2.13	2.13	2.15	2.26	2.14
					45.0	3.21	3.18	3.19	3.25	3.34	3.21
		Landside	5	2	38.7	1.24	1.39	1.41	1.26	-	-
			15			1.24	1.39	1.39	1.25	-	-
			25			1.24	1.39	1.34	1.22	-	-
			40			1.24	1.37	1.25	1.15	-	-
			60			1.24	1.18	1.09	0.98	-	-

Table 10. Factor of safety for Albuquerque, NM, levee (landside) tree locations at the toe and one floodwater levels, without wind load (β = 0.01).

Location	Tree Species	Failure Slope	Wind Speed (mph)	Failure Criteria	Drain Blockage (%)	Water Level (ft)	Factor of Safety	
							No Tree	Tree at Toe
Albuquerque, NM	Fremont cottonwood *(Populus fremontii)*	Landside	0	2	0	4222	2.27	2.07
					25		2.27	1.99
					50		2.27	1.98
					75		2.27	1.98
					100		2.27	1.97

The three-dimensional analysis shows the potential for local modifications to the seepage and soil mechanics for different scenarios using the 3-D model. Without more detailed characterization of the actual material properties (hydraulic and structural) of the root-soil system, it is difficult to make conclusions. If the root-soil system has significantly enhanced strength, the sensitivity study indicated that the factor of safety would increase. If the root-soil system has reduced hydraulic conductivity without enhanced strength, then the factor of safety could actually be reduced due to the higher pressure gradients.

Table 11. Stability sensitivity study in 3-D analysis to root system strength.

Unmodified root system	$\beta = \Gamma = 1$	FS = 0.9
Low hydraulic conductivity root system and unmodified strength	$\beta = 0.001$ $\Gamma = 1$	FS = 0.8
Low hydraulic conductivity and strengthened root system	$\beta = 0.001$ $\Gamma = 10$	FS = 1.1
Low hydraulic conductivity and strengthened root system	$\beta = 0.001$ $\Gamma = 100$	FS = 1.1
Low hydraulic conductivity and strengthened root system	$\beta = 0.001$ $\Gamma = 1000$	FS = 1.1

FS = factor of safety

The three-dimensional modeling methods described in Volume III reached a level that exceeds current capabilities to define material properties in sufficient detail. For modeling to reach its fullest potential, more precise material characterization through both measurements and constitutive theory for root-soil systems is needed.

The underlying question is, “Does woody vegetation affect levee performance?”

The complexity and variability associated with root systems, soils, climate, geography, and geology poses impossibility in answering this question with a single, definitive answer with this initial research. There are still many realms in which further research is needed to advance the science, not only as it relates to woody vegetation, but to soil mechanics as well. However, the importance of this question is fully realized and is answered based on ERDC research involving specific sites.

Trees and their root systems were found to have an effect on overall levee stability. Results indicated that a tree can increase or decrease the factor of safety with respect to slope stability depending on the location of the tree on the levee. Additionally, when wind speeds greater than 40 MPH are considered, the factor of safety decreases for all tree locations evaluated for this study (top of slope, mid slope, and toe of slope). In this study, reductions in the factor of safety reflect specific conditions and may not represent the worst case scenario at these sites. Because of the extreme variability in geology, tree species, climate, and soils, the impact of trees on levees must be analyzed on a case-by-case basis. However, this study does reveal that the tree weight, tree location, root system, and wind loads are all significant parameters that must be taken into account when evaluating the effect of a tree on slope stability for a particular site.

The effect of roots on stability from seepage-related failure has two components. First, there is the issue of the effect the root mass has on the overall flow field. The sensitivity studies consistently showed that the disturbance in the flow field is restricted to the immediate area of the root mass. Thus, if the flow field and pressure conditions are within the bounds of safety without woody vegetation, it will be equally safe if live woody vegetation is present.

The second issue of how of the root mass might cause local regions of high flow that could initiate unstable localized internal erosion is more difficult. For while general seepage analysis was a mature technology even before the advent of the computer, the ability to predict instabilities created by internal erosion has lagged far behind. There is general knowledge about soil types most susceptible to piping, the role of hydraulic gradient to move fine material, and the evolution of the piping process. That knowledge does not support making quantitative predictions of the possible failure modes. Such predictions are not beyond current computational capabilities, but the fundamental studies needed to capitalize on those capabilities have not been performed. Data are needed to define the mechanics involved and to develop equations that describe the processes. Computer models are needed, and extensive model verification based on laboratory and field tests must be performed. Such models would apply to levee stability in general and could be justified apart from the issue of what effect woody vegetation has on the problem. In the absence of a predictive model, the issue of initiation can be reasoned based on what it means to be stable. Conditions are unstable when localized internal erosion can propagate from a point of initiation. It is the condition of the foundation that permits the initiated feature to grow that is the problem, not the initiator itself. The unstable condition is a function of soil type and pressure field. As already stated, the pressure field is only affected locally by the presence of roots and thus does not contribute to the general instability condition. Other factors, such as past performance of the levee and presence of sand boils, should also be considered before a final statement of the effects of woody vegetation on a levee.

6 Recommendations

The following are recommendations that may be derived from this study; however, it should be noted that different species and soil conditions may respond differently to field investigation techniques:

- Electrical resistivity imaging techniques provide the best geophysical method for determining the minimum extent of a root system across a range of environmental conditions, and should be considered in further investigations of bulk properties of root systems. Conversely, in favorable environmental conditions, ground penetrating radar showed promise for detection of individual roots.
- Two-dimensional, limit equilibrium analysis tools are capable of modeling the effects of tree roots and tree mass on slope stability. In fact, current literature suggests using limit equilibrium methods to model the reinforcing effects of the roots and the driving force of the tree mass in limit equilibrium stability models. However, this study found that limit equilibrium models are not capable of accurately representing large lateral wind loads, and stress-strain based models (finite difference, finite element) more accurately account for these loads in a slope stability analysis.
- The factor of safety was slightly reduced when trees were located at the crest and mid-slope locations on the land side of the levee in the numerical models. This result is intuitive because the tree mass contributes to the driving force causing slope failure. However, the small variations in factor of safety are a direct reflection of the moderate tree mass selected for this study. Larger reductions in the factor of safety are expected as tree mass increases.
- According to the numerical models, when the tree was located at the levee toe (either side), a reinforcing effect was observed and the factor of safety was increased. Reinforcing effects appear to be limited to the area just below the roots. The increase in stability from a tree at the levee toe is due to the tree acting as an anchor and counter weight against sliding. However, this study did not take into account wind throw, and a tree at the toe is the critical location for wind throw affecting global levee stability.

- The effects of tree roots on other levee failure mechanisms, such as wind throw, internal erosion, and scour, should be investigated to determine the full impact of trees on the performance of levee systems.
- Failure mechanisms related to internal erosion and piping should be investigated through a combination of model studies and review of case histories. At present, standard methods of seepage and slope stability analysis do not capture these progressive mechanisms, limiting the ability to make rational risk-based assessments. Development of rational methods of predicting progressive failure by internal erosion, piping, and general suffusion would benefit the study of vegetation and the evaluation of levee safety in general.
- Research into the influence of a root system on macroporosity should be investigated in extensive field studies to better understand the complexities of root and soil interaction.

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Appendix A: Glossary[1]

A

Alluvial Deposit
Clay, silt, sand, gravel, or other sediment deposited by the action of running or receding water.

Alluvium
A general term for all detrital deposits resulting directly or indirectly from the sediment transported by (modern) streams; thus including the sediments laid down in river beds, floodplains, lakes, fans, and estuaries.

B

Bank
(1) The rising ground bordering a lake, river, or sea; or of a river or channel, for which it is designated as right or left as the observer is facing downstream.

Baseline
The primary reference line defining a construction coordinate system.

Bathymetry
The measurement of water depths in oceans, seas, and lakes; also information derived from such measurements.

Bed
The bottom of a watercourse, or any body of water.

Bedrock
The solid rock that underlies gravel, soil, and other superficial material. Bedrock may be exposed at the surface (an outcrop) or it may be buried under a few centimeters to thousands of meters of unconsolidated material.

Bench Mark
A permanently fixed point of known elevation. A primary bench mark is one close to a tide station to which the tide staff and tidal datum originally are referenced.

Berm
On a structure: a nearly horizontal area, often built to support or key-in an armor layer.

Boil
An upward flow of water in a sandy formation due to an unbalanced hydrostatic pressure resulting from a rise in a nearby stream, or from removing the overburden in making excavations.

Boring
A hole advanced into the ground by means of a drilling rig.[1]

[1] These definitions are from references listed following this glossary.

Breaching
(1) Formation of a channel through a barrier spit or island by storm waves, tidal action, or river flow. Usually occurs after a greater than normal flow, such as during a hurricane. (2) Failure of a dike allowing flooding.
Bulk density
Bulk density is the mass of material per unit volume.

C

Channel
A natural or artificial waterway of perceptible extent which either periodically or continuously contains moving water, or which forms a connecting link between two bodies of water.
Clay
A fine grained, plastic, sediment primarily composed grains consisting of clay minerals. For purposes of engineering classification, clay is identified as having the size fractionless than 0.004 mm. Clay particles possess electromagnetic properties that bind the grains together to give cohesion.
Cohesive Sediment
Sediment containing significant proportion of clays, the electromagnetic properties of which cause the sediment to bind together.

D

Datum
A horizontal or vertical reference system for making survey measurements and computations. The vertical datum used in the United States is the National Geodetic Vertical Datum of 1929 (NGVD 29), formerly referred to as the Sea Level Datum of 1929. This datum has been upgraded to the North American Vertical Datum of 1988 (NAVD 88).
Degradation
The geologic process by means of which various parts of the surface of the earth are worn away and their general level lowered, generally by the action of wind and water.
Digital Elevation Model
A topographic/geospatial data set of a project area. The DEM is usually a gridded model at constant post spacing.
Dike
In most areas of the United States, a structure (earth, rock, or timber) built part way across a river for the purpose of maintaining a navigation channel. In other areas, the term is used synonymously with levee. Dikes are generally constructed of earth, stone, timber, concrete, or similar material.
Discharge
The discharge, usually abbreviated as "Q", is the volume of a fluid or solid passing a cross section of a stream per unit time.

E

Embankment
Fill material, usually earth or rock, placed with sloping sides and with a length greater than its height. Usually an embankment is wider than a dike.

Eolian (also Aeolian)
Pertaining to the wind especially used with deposits such as loess and dune sand, and sedimentary structures like wind formed ripple marks.

Erosion
The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.

F

Flood
Abnormally high water flows or water level that overtops the natural or artificial confining boundaries of a waterway. A general and temporary condition of partial or complete inundation of normally dry land areas from the overflow of river and/or tidal waters and/or the unusual accumulations of waters from any sources.

Floodplain
A flat tract of land bordering a river, mainly in its lower reaches, and consisting of alluvium deposited by the river when the river overflows its banks.

Flood Stage
The water surface elevation of a river, stream, or body of water, above which flooding and damages normally begin to occur, normally measured with respect to a specific reference gage. Flood stage is normally the level at which a river overflows its banks. Flood stage for any particular geographic area is unique to that geographic area.

Fluvial
Of or pertaining to rivers; produced by the action of a river or stream (e.g., fluvial sediment).

G

Geographical Information System (GIS)
Database of information which is geographically referenced, usually with an associated visualization system.

Geotechnical Investigations
Subsurface investigation of soils, rock, and other strata for the purposes of engineering design.

Global Positioning System (GPS)
A navigational and positioning system developed by the U.S. Department of Defense, by which the location of a position on or above the Earth can be determined by a special receiver at that point by interpreting signals received simultaneously from several of a constellation of special satellites.

Gradient
A dimensionless measure of slope (soil- or water-surface) in distance of rise or fall per horizontal distance.
Gravel
Unconsolidated natural accumulation of rounded rock fragments coarser than sand but finer than pebbles (2 to 4 mm diam).
Ground-penetrating radar (GPR)
The use of high frequencies of electromagnetic waves that are propagated in a straight line into the ground to depths which vary from a few feet to tens of feet, depending on the electrical conductivity of the terrain. The use of GPR is similar to the seismic reflection technique because both methods record the time required for a wave to travel to an interface between two formations and then reflect to the surface.
Groundwater
The water contained in interconnected pores of sediments located below the water table.

H

Head, Total Hydraulic
The sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer.
Hydrograph
A continuous graph showing the properties of stream flow with respect to time.
Hydraulic Conductivity
The rate at which water of a specified density and kinematic viscosity can move through a permeable medium under a hydraulic gradient of one.
Hydraulic Gradient
The change in total head with a change in distance in the direction that yields a maximum rate of decrease in head.

I

Infiltration
Water entering the groundwater system throughout the land surface.

J K

L

Natural Levee
(1) A ridge or embankment of sand and silt, built up by a stream on its floodplain along both banks of its channel.
Light Detection And Ranging (LIDAR)
Laser range and distance measurements of the earth from an aircraft; can be used to generate a dense grid of elevation points for various mapping products to include DEM, and DTM data sets.

Load
The quantity of sediment transported by a current. It includes the suspended load of small particles and the bed load of large particles that move along the bottom.

M

Mean Sea Level (MSL)
A tidal datum which is the mean of hourly water elevations observed over a specific 19-year metonic cycle (the National Tidal Datum Epoch).

Mud
A fluid-to-plastic mixture of finely divided particles of solid material and water.

N

O

Overtopping
Passing of water over the top of a structure as a result of wave runup or surge action.

P

Permeability
The property of bulk material (sand, crushed rock, soft rock in situ) which permit movement of water through its pores.

Piezometer
A nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface. A piezometer generally has a short well screen through which water can enter.

Piping
Erosion of closed flow channels (tunnels) by the passage of water through soil; flow underneath structures, carrying away particles, may endanger the stability of the structure.

Pore Pressure
The interstitial pressure of water within a mass of soil or rock.

Porosity
Percentage of the total volume of a soil sample not occupied by solid particles but by air and water, = Vv/VT × 100.

Q R

S

Sand
Sediment particles, often largely composed of quartz, with a diameter of between 0.062 mm and 2 mm, generally classified as fine, medium, coarse

or very coarse. Beach sand may sometimes be composed of organic sediments such as calcareous reef debris or shell fragments.

Saturation

(1) Soil saturation. A condition in soil in which all spaces between the soil particles are filled with water. Such conditions normally occur after prolonged periods of rainfall and/or snowmelt. (2) Levee saturation. Soil saturation that has occurred in an earthen levee because of floodwaters remaining above flood stage for extremely long periods of time. This condition can lead to catastrophic failure of the levee.

Sediment

(1) Loose, fragments of rocks, minerals or organic material which are transported from their source for varying distances and deposited by air, wind, ice and water. Other sediments are precipitated from the overlying water or form chemically, in place. Sediment includes all the unconsolidated materials on the seafloor. (2) The fine grained material deposited by water or wind.

Seepage

The movement of water through small cracks, pores, interstices, out of a body of surface of subsurface water. The loss of water by infiltration from a canal, reservoir or other body of water or from a field. It is generally expressed as flow volume per unit of time.

Seepage Velocity

Also known as pore water velocity. The rate of movement of fluid particles through porous media along a line from one point to another.

Silt

Sediment particles with a grain size between 0.004 mm and 0.062 mm, i.e., coarser than clay particles but finer than sand.

Soil

A layer of weathered, unconsolidated material on top of bedrock; in engineering usage soil refers to all sediments that carry load through unbound grains; in geologic usage, soil is usually defined as containing organic matter and being capable of supporting plant growth.

Stage

The elevation of a river or confined water area, usually referred to a low water datum plane.

T

Thalweg

The line following the lowest part of a valley, whether under water or not. Usually the line following the deepest part, or middle, of the bed or channel of a river.

U

Unconsolidated

In geologic usage, unconsolidated refers to sediment grains, loose, separate, or unattached to one another.

Universal Transverse Mercator (UTM) Coordinate System

A worldwide metric military coordinate system rarely used for civil works applications.

Unsaturated Zone

Also known as the zone of aeration and the vadose zone. The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched groundwater, may exist in the unsaturated zone.

V

W

Water Level

Elevation of still water level relative to some datum.

Water Table

The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending just into the zone of saturation and then measuring the water level in those wells.

X Y Z

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