ERDC TR TO HQUSACE

Engineer Research and Development Center

US Army Corps of Engineers®
Engineer Research and Development Center

# Initial Research into the Effects of Woody Vegetation on Levees

## Volume I of IV: Project Overview

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

July 2011

Prepared for Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

ERDC TR TO HQUSACE
July 2011

# Initial Research into the Effects of Woody Vegetation on Levees

## Volume I of V: Project Overview

Maureen K. Corcoran, John F. Peters, Joseph B. Dunbar, Jose L. Llopis, Johannes L. Wibowo, Janet E. Simms, M. Eileen Glynn, Bryant A. Robbins, Ryan C. Strange, and Landris T. Lee

*Geotechnical and Structures Laboratory*
*U.S. Army Engineer Research and Development Center*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

Fred T. Tracy

*Information Technology Laboratory*
*U.S. Army Engineer Research and Development Center*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

S. Kyle McKay, Martin T. Schultz, Thomas E. Berry, Joan U. Clarke, and J. Craig Fischenich

*Environmental Laboratory*
*U.S. Army Engineer Research and Development Center*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

Christopher E. Kees, Matthew W. Farthing, and Charles D. Little

*Coastal and Hydraulics Laboratory*
*U.S. Army Engineer Research and Development Center*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

Final report

Prepared for Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

# 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 $\beta$, ranging from 1,000 to 0.001. When $\beta$ 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.

**DISCLAIMER:** The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

**DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.**

# Contents

# Figures and Tables

## Figures



## Tables

# Preface

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

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

The research direction was provided by Dr. Michael K. Sharp, ERDC Technical Director for Water Resources Infrastructure (WRI) and Dr. Maureen K. Corcoran, Associate Technical Director for WRI. This publication was prepared under the general supervision of Dr. David W. Pittman, Director, GSL.

At the time of publication of this report COL Kevin Wilson was Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was Director.

This volume is one of four volumes documenting research conducted by 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, geology, and soils within and underlying the levee); field studies (including tree properties and identification), and estimation of root and root ball dimensions using electrical resistivity, electromagnetic induction, 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 (U.S. statute) | 1,609.347 | meters |
| miles | 1.61 | kilometers |

# Acknowledgements

The U.S. Army Engineer Research and Development Center (ERDC) would like to acknowledge and greatly thank the support of many individuals who contributed their time and resources to ensure the success of this research. The following engineers and scientists from the U.S. Army Corps of Engineers (USACE) Districts and Divisions were instrumental in providing input on field locations, local knowledge of woody vegetation, field support, and geotechnical reports; U.S. Army Engineer District, Albuquerque (SPA) – Ondrea C. Hummel, William J. Trujillo, Deborah A. Foley, Bruce A. Jordan, Kristopher T. Schafer, Dwayne E. Lillard (retired); U.S. Army Engineer District, Sacramento (SPK) – Mary P. Perlea, Kevin Knuuti, Mee-gan G. Nagy, Michael D. Ramsbotham, Edward A. Ketchum, Pamlyn K. Hill, Ben Gompers; U.S. Army Division, South Pacific Division (SPD) – Kennith G. Harrington, Lester Tong (retired); U.S. Army Engineer District, New Orleans (MVN) – Stephen F. Finnegan, Michael L. Stout (Contractor); Mississippi Valley Division (MVD) – Ken Klaus; U.S. Army Engineer District, Portland (NWP) – Les D. Miller; U.S. Army Engineer District, Ft. Worth (SWF) – Anita Hill, Ramanuja C. Kannan, Les Perrin (retired); U.S. Army Engineer District, Seattle (NWS) – Charles H. Ifft, Douglas T. Weber, Catherine A. Desjardin; Northwestern Division (NWD) – Steven J. Fink ; and U.S. Army Engineer District, Jacksonville (SAJ) – Randy L. Rabb.

In addition to the principal investigators listed as authors of this report, the following people at ERDC and its contractors supported field efforts, literature searches, and data analyses and are gratefully acknowledged: Dr. Monte L. Pearson Raju V. Kala, Isaac J. Stephens, Clinton J. Forsha, and Jerry Ballard, ERDC, Geotechnical and Structures Laboratory; Jim A. Dolan, ERDC, Information Technology Laboratory (ITL); Daniel A. Leavell, Bowhead Science & Technology; Dr. David Biedenharn and Dr. Chester Watson, Biedenharn Group; Rae Gore and Chelsea Thomas, Bevilacqua Research Corporation; Lyndsey Freeney and Daniel Chausse, ERDC-Contractors; Pam Bailey, Bobby W. McComas, Tyler D. Tharp, Megan English, and Leah McMahon, ERDC, Environmental Laboratory.

Cheri T. Loden, InfoPro; Marilyn Holt and Karen Taylor, U.S. Army Corps of Engineers-Information Technology Laboratory, compiled and formatted the report. Mark Hardenberg, (STEM International), Bill Mullen (Bowhead Science & Technology), and Pamela Harrion (ITL) edited the report.

Agencies and individuals outside of USACE were outstanding in their support of our research. The ERDC field activities could not have been completed without the assistance of the following people and organizations: Danville, PA - Tom Graham, Danville Bureau Secretary, Joe V. Bellini, AMEC, Scott Raschke, Schnabel Engineering; Albuquerque, NM – Jerry Lovato, Albuquerque Metropolitan Arroyo Flood Control Authority, Ray Gomez, Middle Rio Grande Conservation District, Mark Stone and students, (University of New Mexico); Sacramento, CA – Richard E. Marshall (retired), California Central Valley Flood Control Association), Dr. Alison Berry, Shih-Ming Chung, and Jaylee Tuil, University of California (UC)-Davis, Roy Kroll, California Department of Water Resources, and River Partners; Jacksonville, FL – Steve Partney, South Florida Water Management District; Burlington, WA – Chuck Bennett, Skagit River Drainage District No. 12; Portland, OR – Dave Hendricks, Multnomah County Drainage District No. 1; and Vicksburg, MS – James Marble, Vicksburg Sand and Gravel.

The participation of Ben Gouldby, HR Wallingford, UK, and Dr. Kenneth Cumming, National Marine Fisheries Service, in the ERDC/California Science Team workshop is greatly appreciated. The expertise of John Greenwood, University at Nottingham-Trent, UK, on root pullout tests greatly increased our knowledge of the procedure and data analysis. Dr. Philip Soar, University of Portsmouth, UK, is acknowledged for his detailed review of a root system model. We appreciate the time Dr. Natasha Pollen-Bankhead and Dr. Andrew Simon, U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, spent relating their experiences on permeameter tests. Loren Murray, URS Corporation, provided the Light Detection and Ranging (LiDAR) scans for the Pocket Levee in Sacramento, CA.

A special thanks to the California Science Team for the many discussions and their input concerning this research; George Sills, Sills Engineering, Dr. Leslie F. Harder, Jr., HDR Engineering, Inc., Dr. F. Douglas Shields, Jr., Consulting Hydraulic Engineer, Keith Swanson, California Department of Water Resources, Laura Kaplan, Center for Collaborative Policy, Dr. Donald Gray, University of Michigan, Peter Buck and Mick Klasson, Sacramento Area Flood Control Agency, Dr. Alison Berry, UC-Davis, Dr. Chris Peterson, University of Georgia, Roy Kroll and Mike Inamine, California Department of Water Resources, Dr. Jonathan Bray, University of California, Berkeley, Sujan Punyamurthula, Richard Millet, and Franz Campero, URS Corporation, and Steven Chainey, AECOM.

# 1 Introduction

The research conducted by the U.S. Army Engineer Research and Development Center (ERDC) to assess certain effects of living woody vegetation (trees) on levees is documented in four volumes as follows:

Volume I: Project Overview
Volume II: Field Data Collection
Volume III: Numerical Model Simulation
Volume IV: Summary of Results and Conclusions

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. Major components of this project include site selection, root characterization, and analysis (including levee location, geometry, geology, and soil classification within and underlying the levee); field studies (including root properties), estimation of root ball dimensions using electrical resistivity, electromagnetic induction, and ground-penetrating radar, as well as root excavation; and numerical simulation modeling (including sensitivity and deformation analyses).

This report is divided into topics based on the project scope of work (SOW) approved by Headquarters, U.S. Army Corps of Engineers (HQUSACE), in October 2009. The SOW approach is discussed in more detail in Chapter 4 of this volume. Figure 1 is a flowchart outlining each task, and the volume number where the details of each task are located.

## Background

In addition to inhibiting flood fighting, inspection, and maintenance activities, some of the potential negative effects of woody vegetation are that root growth penetrating into and extending underneath the levee structure might provide a preferential route for seepage flow; root growth and decay may lead to creation of macropores and subsequent piping; and large trees may be more susceptible to windthrow and mass failure. However, healthy root systems might serve to strengthen potential slope stability failure planes within and around a levee, and, as a result, might push failure planes deeper into the levee structure, thereby lengthening potential failure planes and effectively increasing the slope stability of the system.

In July 2007, ERDC conducted an extensive literature review focusing on the effects of woody vegetation on levees at the request of HQUSACE. Based on the literature review, HQUSACE recognized that research was needed to provide scientific and engineering input to better understand the impact of woody vegetation on levees. In April 2008, HQUSACE requested that ERDC begin research on this issue. ERDC formed a team 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 SOW introduced in this volume was structured from scientific and engineering data gaps found after an extensive literature review was completed and also in an effort for research to inform USACE guidance on woody vegetation on levees.

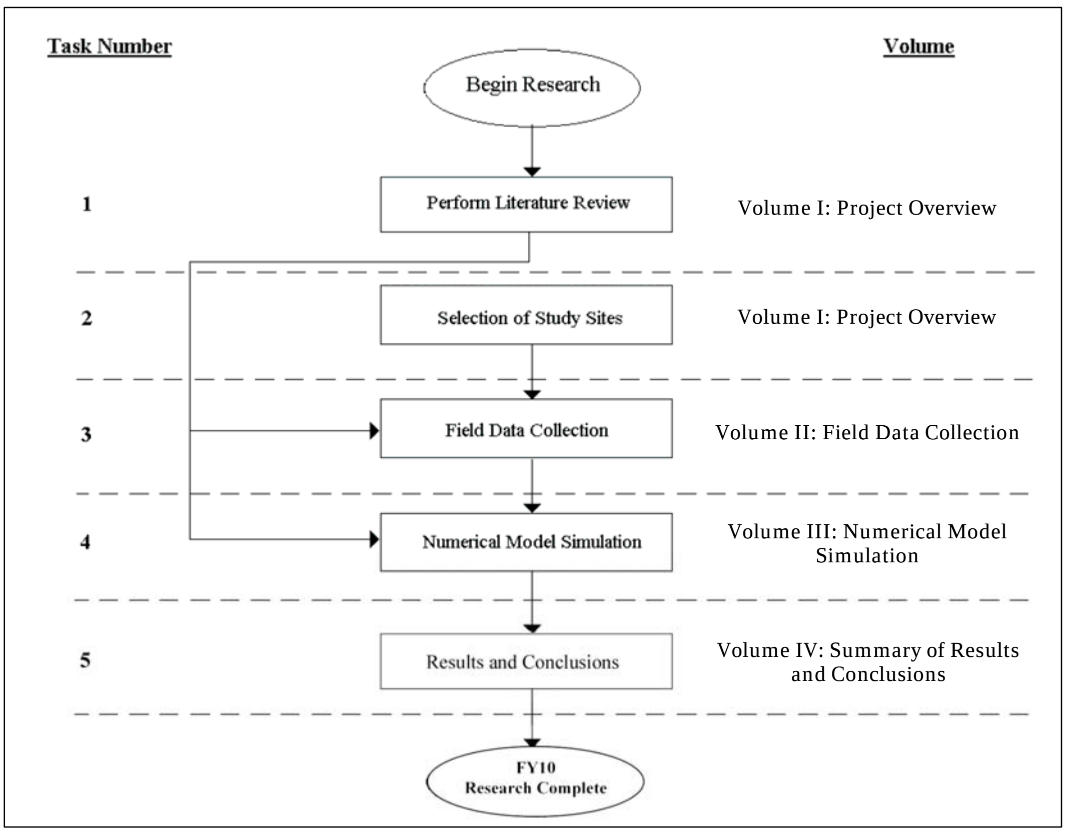



Figure 1. Flowchart of the ERDC research approach.

In this research, parameters associated with living, healthy trees were used in the analyses. Root decay in living trees was not included in this study. In this research, the effect of a living isolated tree on the initiation of internal erosion and on slope stability were studied. The research is not intended to weigh positive versus negative effects of woody vegetation on levees.

According to the Federal Emergency Management Agency (FEMA 2005), woody vegetation is defined as plants that develop woody trunks, root balls, and root systems that are not as large as trees, but cause undesirable root penetration in dams. Under the ERDC research, the definition of woody vegetation includes trees, but it is possible that root systems of shrubs might also produce the same effect on the soil profile as root systems from trees.

## Purpose

The purpose of this research is to conduct initial research using scientific and engineering methods on the impact of woody vegetation on slope stability and the initian of internal erosion on a levee profile for a select number of levees in the United States. The variability in levee systems, soil profiles, geography, and tree species is tremendous and difficult to analyze even with extensive research programs. Therefore, results from this research are not applicable to all levee systems or tree species. This research provides information regarding the impact of trees on slope stability and the imitation of seepage on a levee profile, but included only individual trees in the analyses and did not consider the impact of multiple trees at one location.

In addition, the research described in this report includes techniques for investigating the complicated interactions of woody vegetation with an often complex environment in both subsurface and surface regimes. Other methods or tools not mentioned in this report are available to study woody vegetation on levees. Field methods used in this study are described in Volume II.

The project SOW was formulated using input from USACE scientists and engineers, coordination with academia and international governments, and independent review of the research scope of work. Workshops were held to bring world-renown leaders in geotechnical and vegetation modeling together for input and review of the research plan. An independent review of an abbreviated research SOW was coordinated by Battelle at the request of HQUSACE. Consultants hired by Battelle suggested minor changes to the scope of work.

In addition to an independent review, ERDC met with John Greenwood, University of Nottingham-Trent, UK, to discuss the application of SLIP4EX to slope stability analysis. SLIP4EX is a computer program developed by John Greenwood under the ECOSLOPES project for routine stability analysis and assessment of the contribution of vegetation to slope stability. The discussion was helpful in formulating field data collection, and conducting subsequent model studies. The SLIP4EX model was used for the initial slope stability analyses in this research, but the model used in the final analysis, and discussed in Volume III, was the robust UTEXAS4. The analysis using SLIP4EX are not discussed in this document.

The efforts reported in this research were focused on living, healthy woody vegetation, and apply to sandy or silty sand levees. Research included a single tree in the analyses and did not consider the impact of multiple trees at one location. Levees consisting of clay were not included in the numerical analyses for this study. 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 SOW 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; and the role of woody vegetation contributing to scour and erosion. The effect of woody vegetation on levee inspection, and maintenance, and accessibility to the levee for flood fighting were also not considered in this study. Although not addressed, the need for research in these areas is recognized by the USACE.

# 2 Literature Review

## Previous research on woody vegetation

Levee failures, and resulting destruction caused by Hurricane Katrina in 2005, prompted a resurgence of the decades old question—How does woody vegetation affect the structural integrity of a levee and, hence, levee performance?

This section briefly describes previous research relevant to the ERDC scope of work. Corcoran et al. (2011) provide a more thorough review of documents addressing the effects of woody vegetation on levees and related subjects.

### Repair, Evaluation, Maintenance, Rehabilitation (REMR) research

The most comprehensive research on the effects of woody vegetation on levees is included in a series of reports (Gray et al. 1991; USACE 1988a; USACE 1988b) published by ERDC under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

The REMR research used a cumulative evaluation of slope stability, root profile, grain-size distribution, botanical data, and soil type. The technique used to study root systems involved excavating trenches parallel and perpendicular to the levee trace to view roots in cross section. Root area ratios were derived from these cross sections and plotted with respect to the depth of a root segment.

The REMR studies found that, for sandy, overbuilt levees, roots of woody plants could reinforce the levee soil and measurably increase shear strength. Furthermore, it was found that allowing woody vegetation to grow on the inclined banks of the levee did not hinder access to service roads along the crown.

Research conducted under REMR also spawned journal articles and conference proceedings authored by REMR principal investigators, Dr. Donald Gray and Dr. Doug Shields. Shields et al. (1989) provided an overview of current issues in the management of vegetation on levee embankments, concluding that site-specific management of levee woody vegetation allows for multi-use of levees without decreasing their structural integrity. Based on gathered field observations, Shields et al. (1989) discussed the justification for USACE standards of allowing just enough vegetation to provide soil-holding capacity, but he also recognized that additional knowledge is needed about vegetal components within a geotechnical system.

Gray et al. (1991) found “that in situ shear strength measurements showed that roots increased soil shear strength and that slope stability analyses indicated larger vegetation made levees more secure” on sandy levees along the Sacramento River. As Shields et al. (1990) mentioned, however, past research was not “adequate to assess vegetal effects on seepage and piping potential” and also noted that inspection issues were not addressed.

Shields and Gray (1992) used field data and slope stability analysis from a 10-km segment of a channel levee on the Sacramento River near Elkhorn, CA, to conclude that “allowing woody shrubs and small trees on levees would provide environmental benefits and would enhance structural integrity without the hazards associated with large trees, such as windthrowing.”

As a result of the REMR study, USACE (1988a) concluded that “vegetation management on levees is a complex issue and few data exist on the influence of vegetation on the structural integrity of levees.” They noted that “before revising the USACE standards, additional knowledge must be developed regarding vegetal components of the geotechnical system.”

Although the method used in the REMR study for identifying the effects of woody vegetation on soil strata was well accepted prior to the 21st century, it did not account for root systems in three-dimensions (3-D). To the advantage of today’s researcher, technology and science have advanced, and tools related to soil and root interaction, albeit not on levees, have been developed. Unfortunately, almost 20 years later, research into the effects of woody vegetation on levees has not even slightly advanced. In fact, since the REMR report, there has not been any research on levee woody vegetation at a similar level of effort. However, research has been conducted on woody vegetation outside a levee environment. The following is a brief overview of the significant research developments since the REMR report.

## Root characterization studies

Research on root characterization and the effects of tree roots on slopes is more abundant than studies directed toward woody vegetation on levees. Research discussed in this section was influential in designing the ERDC project. The following discussion is a subset of the reviewed literature. An extensive listing of the literature can be found in Corcoran et al. (2011).

There is terminology that is applicable to research involving trees and, at time, these terms are used interchangeably. “Root biomass” is morphologically characterized separately from the root growth medium (soil matrix). The combination of the growth medium intertwined with the roots is often referred to as the “root ball” or “root wad”. The root biomass structure is explicitly described in terms of “root architecture”, which is the spatial configuration, sizes, and forms of the roots. The soil matrix is not included in an analysis of root architecture. Regardless of the terminology, root architecture (size, shape, depth) of woody vegetation varies significantly with respect to species, soil, slope, depth to groundwater, competition, and many other parameters (Danjon and Reubens 2008). The term “root system” usually refers to the roots proper but may include the growth medium, depending on the purpose of the research. Therefore, the impact of woody vegetation on slope stability and internal erosion is highly case specific.

Although significant progress in analytical, methodological, and theoretical understanding of plant-environment interaction has been made, there is a lack of complete mechanistic understanding of plant-root architecture and function (Barthelemy and Caraglio 2007). In large part, this dearth of subsurface knowledge is driven by challenges in measuring these complex biotic systems and their abiotic and biotic drivers in situ (Fourcaud et al. 2008a). Thus, the inability to accurately and repeatedly measure plant root architecture contributes to countless basic research questions regarding plant growth and function (Fourcaud et al. 2008b), as well as more applied issues such as slope stability (Bibalani et al. 2007; Norris et al. 2007), plant stability under gravitational and wind loadings (Coutts 1983; Danjon et al. 2005; Dupuy et al. 2005; Fourcaud et al. 2008a), influences on seepage and groundwater flows (Chu-Agor et al. 2009), plant-infrastructure interaction (Shields and Gray 1992), and ecological impacts of root structure (Read and Stokes 2006).

An area of importance when studying the effects of woody vegetation on levees is an understanding of the root system. Reubens et al. (2007) and Danjon and Reubens (2008) thoroughly reviewed the variety of techniques for mapping tree-root architecture, which may be coarsely lumped into the following four categories:

1. *Subsampling methods* involve measuring portions of the root system and interpolating or extrapolating conditions to the remainder of the system. Select examples are auger or core sampling (Retzlaff et al. 2001) and trenching (Shields and Gray 1992; Millikin and Bledsoe 1999).
2. *Noninvasive methods* measure the root system with instruments that do not require destroying or unearthing the tree. Select examples are ground-penetrating radar (Hruska et al. 1999; Butnor et al. 2003; Hirano et al. 2008), electrical conductivity (Nadezhdina and Cermak 2003; Cermak et al. 2006a,b), electrical resistivity (Morelli et al. 2007; Amato et al. 2008), and X-ray tomography (Kaestner et al. 2006).
3. *Invasive methods* require the tree to be unearthed and measured in either the field or laboratory. Selected unearthing techniques are manual soil removal (Di Iorio et al. 2005), crane removal of the tree (Danjon et al. 1999), compressed-air soil removal (Danjon et al. 2007), and hydraulic soil removal (Stoeckler and Kluender 1938; Tharp and Muller 1940). Selected measurement techniques are manually measuring coordinates (Henderson et al. 1983), semi-automated digitization using electromagnetic or acoustic devices (Danjon et al. 2007), and laser scanning (Gartner and Denier 2006).
4. *Functional-structural simulation models* estimate root architecture based on ambient environmental conditions (e.g., root absorption) that link growth-driven processes with plant morphogenesis (Fourcaud et al. 2008b).

Each of these techniques has distinct advantages and disadvantages (Reubens et al. 2007; Danjon and Reubens 2008), and selection of a given technique depends on needed resolution of the results, the application environment of interest, and the resource or time constraints of a given project.

Danjon and Reubens (2008) noted that owing to difficulties in accessing roots and duration of the measurements, previous studies examined a low number of root systems and produced qualitative results. They described the improvement in characterization of root properties as a result of the recent advances in 3-D root architecture studies, specifically digitizing tools and software programs that precisely and rapidly measure the full 3-D architecture of uprooted and excavated coarse root systems. One of the techniques they proposed uses an air-lance to loosen and remove soil from around trunks and roots with minor or no damage to the roots. Roots are then digitized in situ or removed for laboratory root mapping. In the laboratory, soil is removed, roots are photographed and digitized, and software designed specifically to model characteristics of a root system in 3-D, such as the French proprietary software AMAPmod, may be used to reconstruct the root system. The central data structure of AMAPmod is a plant representation formalism introduced by Godin and Caraglio (1998). The formalism accounts for plant architectures measured at different scales on different dates and may integrate various types of attributes, geometrical or biological. AMAPmod is now included in OpenAlea, an open source project that integrates many of the individual software programs, including VPlants (Virtual Plants), into one package to include multiscale tree graphs (MTG), statistical analysis, fractal analysis, computer graphics, biophysics, and functional-structural models (Pradal et al. 2007).

Danjon and Reubens (2008) found that noninvasive methods were not as reliable as actually mapping an exposed root system. One of the tools used for noninvasive root mapping is ground-penetrating radar (GPR), a geophysical method that uses radar pulses to image the subsurface. They noted that previous research (Stokes 1999; Butnor et al. 2001; Butnor et al. 2003; Barton and Montagu 2004; al Hagrey 2007) concluded that GPR is useful only for single root segments or biomass estimation with relatively low precision. However, several researchers have used GPR to detect subsurface tree roots. Barton and Montagu (2004) created a test bed using damp sand and buried roots of different diameters at different depths. Under these near-ideal conditions, they were able to detect and model the roots to estimate their diameter. In field applications, researchers have encountered various levels of success, depending on soil type, moisture state and root size, density and depth (al Hagrey 2007; Hruska et al. 1999; Morelli et al. 2007). Danjon and Reubens (2008) further noted that single root segments can be accurately detected by GPR in damp and uniform pure sand, when root segments have low density, and when segments are parallel to the soil surface. GPR output can be directly imported into AMAPmod for visualization.

### Slope stability studies

There are numerous publications on research concerning the effects of woody vegetation on slopes and riverbanks (Riestenberg and Sovonick-Dunford 1983; Watson et al. 1999; Pollen-Bankhead and Simon 2009; Simon et al. 2006). Some studies identify a particular tree species in the research, while others use a generalized approach. Although banks and slopes are not constructed features, it is beneficial to understand the techniques used in these assessments and their potential applicability to the study of woody vegetation on levees. A brief overview of some of this research is given in the following paragraphs.

Endo and Tsuruta (1969) recognized the possibility that tree roots may increase the stability of soils by providing additional shear strength. They performed shear tests of soil inside a 20-in. × 20-in. shear box, first with a root, then with a shear test on similar soil with no root. The difference between the two tests is considered as additional shear strength from tree roots. Endo and Tsuruta, (1969) considered the amount of root, expressed as weight of the root, as an indicator of additional shear strength instead of measuring root tensile strengths.

The effects of roots to shear strength were studied by Wu (1976), who formulated a simple model for calculating additional soil shear strength attributed to roots. Independently, other researchers (Waldron 1977; Gray and Leiser 1982) developed their own models for this same purpose.

Riestenberg and Sovonick-Dunford (1983) studied the stabilizing effects of woody vegetation on slopes in the Cincinnati, OH, area. They conducted stability analyses using the widely accepted infinite-slope analysis (Lambe and Whitman 1969), and computed a factor of safety with both zero root strength and with root strength factors. In their research, they used the thickness of the colluvium cover, average slope angle, unit weight of the soil, angle of friction and cohesion for the soil; and the number, size, distribution, and strength of the roots lying within failure planes to compute the factor of safety. Their method included identifying tree species and a detailed description of the stability analyses. In conclusion, they found that tree roots increased the factor of safety against sliding nine-fold (i.e., nine times as great). More specifically, they reported “root strength allows forested, colluvium-mantled hill slopes in the Cincinnati area to resist sliding at slope angles as high as 35 deg, whereas similar slopes devoid of trees are subject to sliding at slope angles of 12 deg to 14 deg.”

Greenway (1987) conducted one of the most comprehensive literature studies on the effects of tree roots on assessment of slope stability. He suggested that both hydraulic factors and mechanical factors be considered when studying the effects of woody vegetation in a slope stability analysis. According to Greenway (1987), the five mechanical factors to be considered are as follows:

1. The effect of roots in reinforcing soil is to increase soil shear strength.
2. Large roots will act as an anchoring system, holding the weaker upper soil layer to the more stable lower soil layer.
3. Tree weight will give additional vertical load to slope stability calculation.
4. Dynamic wind force on the tree crown will convey horizontal, vertical, and moment load to the slope.
5. Roots will hold soil grains at the ground surface, resisting erosion.

Coutts (2004) noted that tree root systems may bind soil together reducing the chance of erosion and landslides, but that they are also subject to overturning and, therefore, can have negative impacts. These impacts are often critical factors in landslides (and presumably, it may follow that overturned trees may exacerbate the loss of levee integrity).

### Root strength studies

A challenge in studying root reinforcement for soil stability is collecting in situ data on root strength. Abernethy and Rutherfurd (2001) recognized that root reinforcement depends on root tensile strength, interface friction between the root and the soils, and also root distribution within the soil.

Root tensile strength is defined as the ability of a root to hold up against a pulling force parallel to the root length and is described as the maximum force that causes a root break or the pulling force that causes a root to extend to a limited movement. There are two approaches to measure root tensile strength or the pullout resistance of a root: laboratory testing and in situ field measurements. Norris and Greenwood (2003) compared these two approaches, and found that in situ pullout resistance of roots is 50 to 70% lower than actual tensile strength.

Laboratory testing consists of measuring the tensile strength of a tree root using a universal testing machine (Hathaway and Penny 1975; Abernethy and Rutherfurd 2001) or a modified direct shear machine (Tosi 2007). Special root holders clamp both ends of a root to the testing machine.

Tensile strength is increased until the root failed. Although tensile strength is one of the most important measurements of tree root strength, the value obtained from laboratory tests describes only one aspect of the role that tree roots play in slope stability. The other aspect, the effects of root and soil interaction, is evaluated from an in situ pullout test.

Several researchers designed, built, and applied specialized equipment for field measurement of root strength. Norris and Greenwood (2000; 2003) developed and later modified a direct shear and pullout test apparatus to investigate in situ shear strength of soil reinforced by the roots of plants, shrubs, and trees. The 6-in. × 6-in. × 4-in. steel shear box is attached to an aluminum frame. The shear box is connected to a load cell by a steel cable, which is pulled using a hydraulic cylinder. However, to directly measure the force needed to remove a root from the soil, they modified their design for in situ root pullout by replacing the shear box with a root clamping system for holding roots during the pulling process. The displacement is measured using a string potentiometer (pot). Both the load cell and string pot are connected to a portable computer. Using this method, Norris (2005) and Norris and Greenwood (2003) performed pullout tests on roots from oak and hawthorn trees, and then calculated the additional shear strength provided by tree roots using the equation developed by Wu (1976).

Abernethy and Rutherfurd (2001) also designed and used a slightly different device to measure the pullout strength of roots. The device, which they refer to as a jig, was positioned against a trench, previously used for root mapping, to conduct the pullout strength tests. The jig consists of a bearing plate with the center removed for access to the roots. Four legs extend away from the trench wall to a hand-operated boat winch. A bias-woven steel cable sock is used to grip the root ends. Using this jig, Abernethy and Rutherfurd (2001) measured the load exerted against the root with a load-cell connected between the cable-sock and the winch cable. Displacement was measured from the free end of a root with string from a string pot bolted to the bottom of a winch plate and run out to a load cell. Both the string pot and load cell were connected to a data logger. Pollen and Simon (2004) used the root pullout device designed by Abernethy and Rutherfurd (2001) to investigate in situ root tensile strength of riparian vegetation, specifically the roots of both the longleaf pine (*Pinus palustris*) and black willow (*Salix nigra*).

### Post-Katrina levee vegetation studies

In response to the levee failures in New Orleans, LA, from Hurricane Katrina in August 2005, JESCO Environmental and Geotechnical Service, Inc., under the direction of U.S. Army Engineer District, New Orleans, produced a report in July 2008 (JESCO 2008) that detailed their study concerning the effects of trees on levees in New Orleans. Trenches were excavated to construct root profiles for 79 trees; 54 along the three outfall canals in New Orleans, nine trees along levees of Lake Pontchartrain, and 16 trees along the Mississippi River levee. Soil strengths were measured using a penetrometer. JESCO (2008) observed through their study of roots that deep roots are rare. They found that roots having diameters greater than 0.5 in. decreased with depth and that the radial extent of the root ball did not correlate with soil strength. They suggested that a physical model should be used in future research to explore the effects of root channels on outfall levees to complement additional field studies.

### Seepage and piping studies

Although the effect of woody vegetation, particularly the root system, on the stability of slopes is a subject that has been addressed and documented through various geotechnical and bioengineering research efforts, the impacts of woody vegetation on seepage and piping through the levee embankment are much less known. Based on a literature review of existing research, almost no information is available from studies that have attempted to quantify seepage rates attributable to the formation of canals or macropores in the soil embankment as a result of the penetration of roots into the soil embankment (Corcoran et al. 2011).

A study by Sills et al. (2003) of the Sacramento, CA, area levee system identifies deterioration from lack of levee maintenance as a major concern for levee reliability. One of the major factors cited in the investigation by Sills et al. (2003) was the "…emergence of seepage landward of levee induced by animal burrows in the levee top stratum and along the root crown of nearby trees." Contained in this investigation was a report by the U.S. Army Engineer District, Sacramento (Appendix B in Sills et al. 2003), about the lack of vegetation maintenance, and "…seepage distress caused by animal burrows and tree roots."

### Risk-based studies

Brizendine (1997) described a risk-based analysis of levees with woody vegetation using a multiphase approach: performance of laboratory and field test programs, development of hydraulic conductivity probability density functions, and development of a first generation risk model to assess relative risk among groups of levees and to determine rank for systemic allocation of rehabilitation resources. Laboratory tests included using soil from REMR demonstration sites to determine basic soil properties. Soil properties in situ were derived using two-stage borehole tests. Goodness-of-fit tests were then conducted against 21 distributions. Inverse Gaussian, Lognormal, Pearson, Weibull, and Beta statistical methods provided highest-ranking fits for hydraulic conductivity.

Brizendine (1997) used a probabilistic approach based on Monte Carlo simulation to study the slope stability aspect of his research. This method includes determining the critical failure surface using the mean values of cohesion, angle of internal friction, total unit weight, and water table depth. Once the critical failure surface is identified, the Monte Carlo simulation is applied to perform a series of iterations using randomly selected values for the input parameters from the probability distributions. The modified Bishop slope stability analysis is then used to generate a factor of safety. For the seepage analysis, Brizendine used probability distributions for hydraulic conductivities from both the field tests and laboratory analyses. However, he noted that results of tests to determine the effect of woody vegetation on hydraulic conductivity were inconclusive and recommended a more focused study. He also suggested that further development of the risk model should include additional risk branches, such as surface erosion.

# 3 Levee Failure Mechanisms

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. Although the literature provides numerous examples of failure mechanisms, these two failure mechanisms were judged to be the most important to USACE districts in which woody vegetation might affect levee performance.

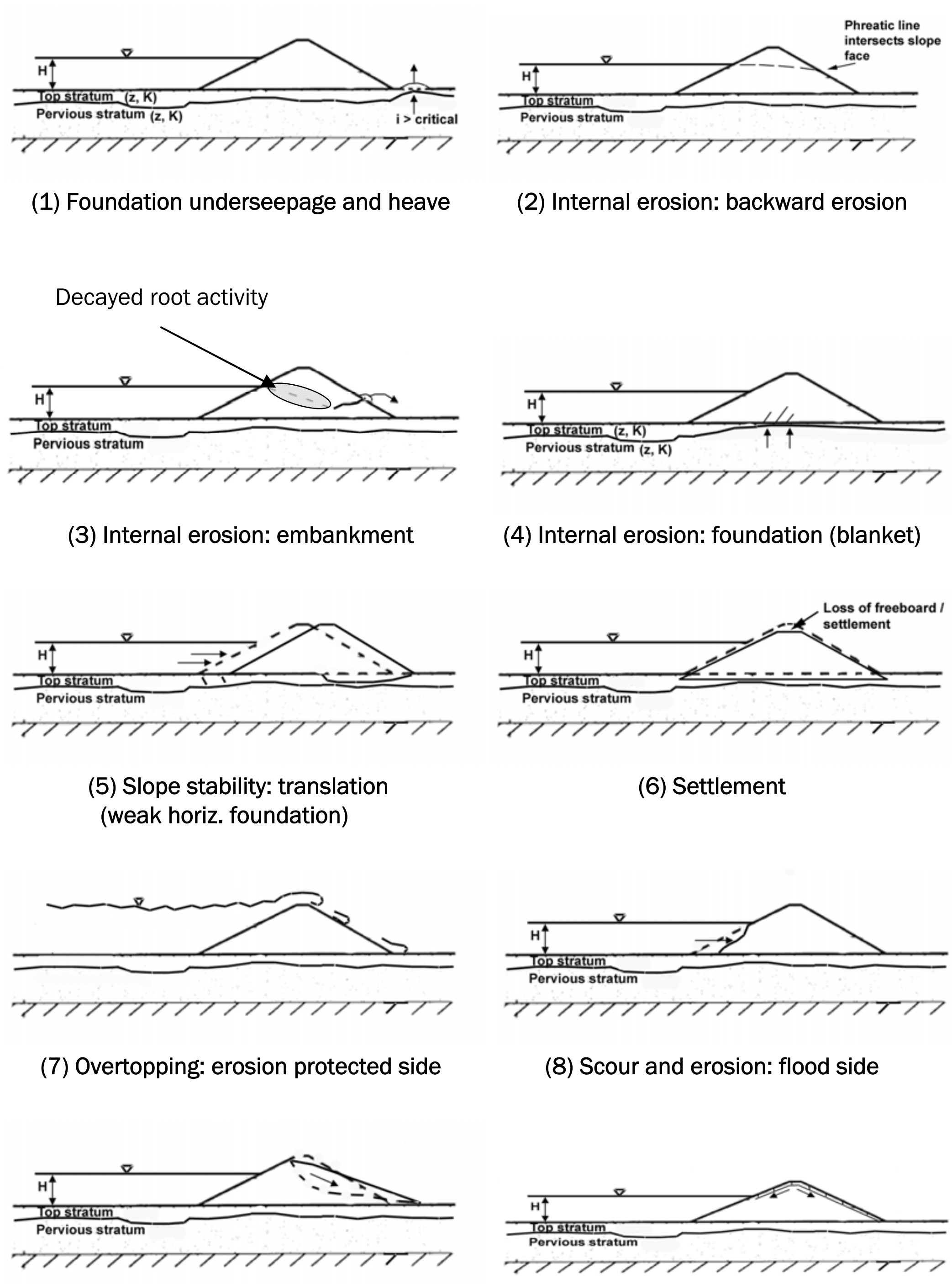
Various authors have used different terminology and levels of resolution in categorizing failure mechanisms. Table 1 provides a sampling of failure mechanisms in the literature. Figure 2 provides diagrams of 10 levee mechanisms; however, as stated in the previous paragraph only mechanisms (4) *internal erosion: foundation* and (9) *slope stability: deep slip plane* were included in the ERDC study.

Schaefer et al. (2010) provide a final draft of a best practices guidance document for estimating probabilities of failure of embankment dams due to internal erosion. This document is of significant value in describing a method and general process for estimating the annual probability of failure by piping and internal erosion. Appendix B1 (in three sheets) of that document provides navigation tables for internal erosion in the soil foundation, which could be relevant to assessing the probability of failure by internal erosion. Table 2 (Sheet 1 of Appendix B1) is provided as an example of the usefulness of this assessment procedure.

In summary, failure mechanisms identified in Tables 1 and 2 illustrate the complexity of the mechanisms involved and the different components of the flood protection system that are impacted. The ERDC research involved the study of the effect of woody vegetation on slope stability, and on 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 seepage and slope stability 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 initial research into a complex issue.

Table 1 Examples of failure mechanisms in the literature.

| Author | Nature of Study | Failure Mechanism |
|---|---|---|
| Vrouwenvelder (1987, in USACE 1999). | Discussed the probabilistic design of dikes and levees in the Netherlands | 1. Overflowing and overtopping<br>2. Macroinstability (deep sliding)<br>3. Microinstability (shallow sliding or erosion of landside slope because of seepage)<br>4. Piping or underseepage |
| USACE (1999) | Discussed the calculation of levee failure probabilities and described failure modes | 1. Slope stability<br>2. Underseepage<br>3. Through-seepage<br>4. Piping<br>5. Surface erosion |
| USACE (2000b) | Engineer Manual Guidance, based on 1956 USACE study. | 1. Overtopping<br>2. Surface erosion<br>3. Internal erosion (piping)<br>4. Slides embankment or foundation |
| Hall et al. (2003) | Described a national-scale flood risk assessment model for the United Kingdom. | 1. Overtopping<br>2. Breaching |
| Steenbergen et al. (2004) | Developed a program to calculate the probability of dike ring failure in the Netherlands | 1. Overtopping and overflow<br>2. Uplifting and piping<br>3. Inner slope failure<br>4. Damage to the revetment and erosion of the dike body |
| Ter Horst et al. (2006) | Constructed a fault tree to estimate the probability of structural failure (breaching) of a dike during a flood wave | 1. Erosion of the inside slope because of overtopping<br>2. Piping<br>3. Instability of the inside slope<br>4. Damage of revetment and erosion of the dike body |
| Allsop et al. (2007) | Described limit-state equations for 72 failure mechanisms for flood defenses, some of which were applicable to earthen levees. Only those failures driven by hydraulic head differentials are listed in this table | 1. Erosion of the surface by overflow<br>2. Bulk sliding or overturning<br>3. Deep slip/slide<br>4. Shallow slip/slide<br>5. Piping and/or internal erosion<br>6. Crest level too low - overflow |
| Vorogushyn et al. (2009) | Described development of fragility curves for earthen fluvial dikes | 1. Piping in the dike foundation<br>2. Slope stability failure caused by through seepage |
| Schaefer et al. 2010 | USACE Internal Erosion Toolbox for Dams | 1. Internal erosion in embankment<br>2. In the foundation<br>3. In embankment and foundation |




(1) Foundation underseepage and heave

(2) Internal erosion: backward erosion

(3) Internal erosion: embankment

(4) Internal erosion: foundation (blanket)

(5) Slope stability: translation (weak horiz. foundation)

(6) Settlement

(7) Overtopping: erosion protected side

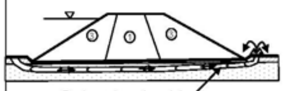
(8) Scour and erosion: flood side

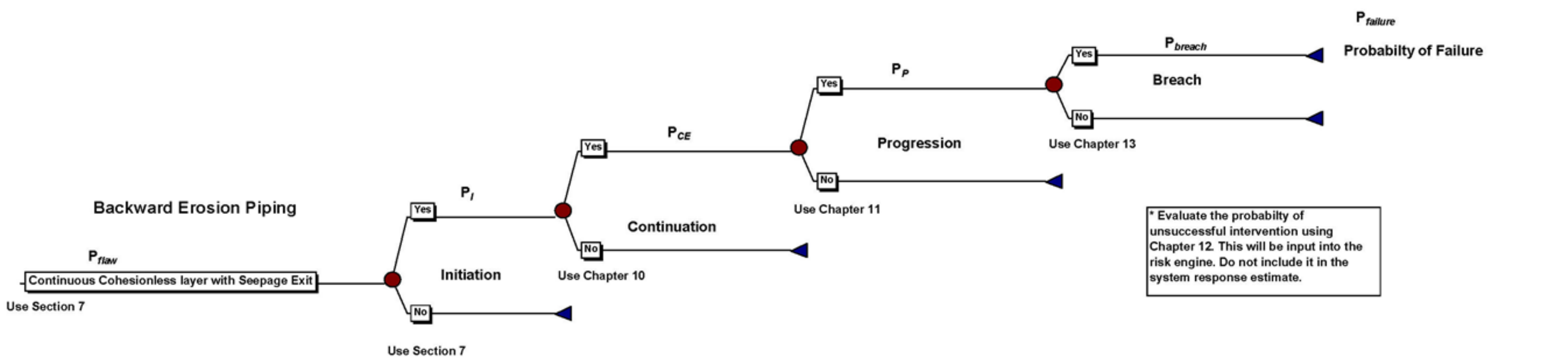
(9) Slope stability: deep slip plane

(10) Slope stability: shallow slides

Figure 2. Only failure mechanisms (4) and (9) are applicable to the present ERDC study.

Table 2. Example of event tree evaluation for internal erosion in foundation in pervious soils (Schaefer et al. 2010).

| Initiating Mechanism | Sketch | (1) Evaluate Probability of a Flaw<br>$P_{flaw}$ | (2) Evaluate the Probability of Initiation of Erosion<br>$P_I$ | (3) Probabilities for Continuing Erosion<br>$P_{CE}$ | (4) Probability of Progression<br>$P_P$ | (5) Probability of Breach<br>$P_{breach}$ | (6) Calculate the Probability of Failure<br>$P_{fail}$ | (7) Probability of Unsuccessful Intervention<br>$P_{ui}$ |
|---|---|---|---|---|---|---|---|---|
| Backward Erosion Piping in Cohesionless Soils<br>**IM22** |  | Determine the probability of continuous cohesionless layer and a seepage exit using Section 7. This is also described in Table B2<br>$P_{flaw}(IM_x)$ | Determine Probability of initiation using Section 7. This is also described in Table B2<br>$P_I$ | Evaluate the probabilities for Continuing Erosion for the failure path under consideration using Section 10<br>$P_{CE}$ | Estimate the probabilities for Progression for the failure path under consideration using Section 11<br>$P_P$ | Estimate the probabilities of breach using Section 13<br>$P_{breach}$ | Calculate the probability of failure for each IM using the event tree<br>$P_{fail} = P_{flaw}(IM_x) \times P_I \times P_{CE} \times P_P \times P_{breach}$ | Estimate the probability for unsuccessful intervention using Section 12 |



# 4 Project Scope of Work

After thoroughly reviewing the failure modes described in the previous chapter and the literature review by Corcoran et al. (2011), a detailed research plan was developed to focus on two categories of failure mechanisms: seepage and slope stability. The possible influence of woody vegetation on these prevalent failure mechanisms are obviously linked with levee performance, and the investigation to support the research on these potential failures provides valuable insight into the interaction of the soil matrix and a root system. For the seepage analysis, the initiation of internal erosion, which may lead to piping, was studied through numerical models based on groundwater and Darcy flow equations. The concentrated seepage, which may occur around a root, was not considered. This research is structured to provide data for future analysis on additional failure mechanisms and to also support requirements for future risk assessment.

The SOW includes: (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 piping and slope stability, under various loading conditions; and (3) developing results and conclusions regarding engineering impacts of woody vegetation on levee performance. Figure 1 is a flowchart of the research approach.

The SOW strongly supports the idea that focused studies of woody vegetation on levees should be conducted in representative areas of the United States and that these studies consider the different geographical and physical characteristics at each site. These characteristics involve regional and local geology, climate, soils, engineering practices, levee construction, performance history, past flooding, and woody vegetation. Therefore, it was important to define the basic characteristics and material properties of the levee embankment, the foundation, and the woody vegetation that are characteristic of different geographical regions and floodplain settings. Each site was also evaluated based on available geotechnical data. Different datums were used at some sites based on documents obtained from the USACE districts. Many river systems in the United States involve a variety of legacy datums and approximated conversions are required to compare different ages of construction. Some of the original project engineering involves older datums and upgrades of the system components may span several datum changes.

Availability and level of detail of the geotechnical data varied greatly for each site. It is important to recognize that adjustments and adaptation were sometimes required to the general research procedure to accommodate different geographic regions and soil regimes.

Research described in the following sections is based on requirements to assess the effects of woody vegetation on levees. The study was designed for nationwide implementation, but because of the extreme variability between the sites the team encountered when collecting field data, it was difficult to specifically define an exact procedure that would be applicable to every geographical region. Given this limitation, this report describes more than one technique for some of the proposed procedures.

The essential tasks underlying the research approach are briefly described as follows:

- **Task 1 – Conduct an extensive literature review:** In August 2007, ERDC conducted a literature review by compiling documents, government reports, international guidance, and journal articles on topics relating to the impacts of the presence of woody vegetation on levees (Corcoran et al. 2011). The literature review was a collaborative effort between ERDC and the California Science Team. The California Science Team consists of the Sacramento Area Flood Control Agency (SAFCA) and its consultants, Department of Water Resources, U.S. Fish and Wildlife, and URS Corporation.

- **Task 2 – Select study sites:** When identifying levee study sites, the team felt it was important to select locations from across the country so that the resulting research would be representative of the varied complexities represented by a vast levee database. However, most of the woody vegetation on levees is found in the western and northwestern part of the United States. Because of this, most of the study sites are located in these regions. Site selection had to consider levee geometry, geotechnical and geological site conditions, and woody vegetation types and spatial distributions of their root systems. In many cases, levee design and construction data, as well as geotechnical and geological data, were fairly well documented by USACE districts. While climate conditions do affect tree growth, the type and species of trees growing along riverbanks and levees is relatively consistent in a given region. Therefore, it was more important to include a fair representation of typical levee systems in which levee geometry, geotechnical, and geological site conditions, such as flood duration, tree species, and root systems, varied.

Field sites are divided into site characterization and site assessment depending on the level of field data collection and numerical analyses. Site characterization consists of conducting quantitative field tests to characterize the subsurface environment, including soil type, soil properties, and geology. A site assessment is a limited field investigation to gather qualitative information on site conditions and root systems.

- **Site characterization.** Geophysical tools were used to define the spatial extent of the root system. Field tests were conducted within the radius of the tree canopy and extended outside the spatial extent of the root system defined by the geophysical assessment. Tests included using a permeameter for measuring hydraulic conductivity variation, a neutron probe for in situ moisture content and unit weight, and pullout tests for measuring root tensile strength. Soil samples were collected for laboratory analyses of physical properties. Because of time constraints to complete the ERDC research, the collected field data were not used to calibrate the models. The selection of sites was based on input from resource agencies, USACE districts, and local levee districts. Field investigations were conducted at the following sites:

  1. Albuquerque, NM: sandy soil, low annual precipitation, sensitive habitat provided by trees
  2. Burlington, WA: sandy clay levees, sensitive salmon habitat provided by trees located on the riverside of the levee on the channel bank
  3. Portland, OR: levee composed of sandy soils; foundation contains a fine-grained top blanket of silt and clay, underlain by pervious substratum composed of silty sands and sand
  4. Sacramento, CA: legacy non-engineered levees built for removing mine tailings, high sand content, cutoff walls installed in 1990s,

sensitive habitat, highest number of maintenance deficiencies related to woody vegetation

- **Site assessments.** In areas where trees were removed to comply with the USACE guidance, qualitative measurements were made and photographs were taken of the root system after tree removal. Soil moisture, unit weight, and hydraulic conductivity were measured in the field. Five sites were selected for assessments at the following locations:

  1. Danville, PA: highly contrasting soil horizons. Trees were removed prior to the ERDC study, but moisture contents on the levee profile were collected.
  2. Boca Raton, FL: levees constructed on limestone, large number of invasive tree species
  3. Lake Providence, LA: field evidence of living cypress tree roots acting as conduits for seepage. These trees are located along an oxbow lake of the Mississippi River and not on a levee. This site is used to observe possible defects that may occur in a soil matrix because of a root.
  4. Lewiston, TX: levee heights similar to Sacramento, but with different geology and levee construction values. Desiccation is a major problem in this area.
  5. New Orleans, LA: high clay content, engineered levees built for navigation.
  6. Vicksburg, MS: sandy soil with gravel deposits; test site for the Light Detection And Ranging (LiDAR) of a root system. This site was not included in the SOW, but was added to accommodate testing of LiDAR for its applicability in root characterization.

- **Task 3 – Collect field data:** Data collected for this project were selected on the basis of published research and knowledge gained by collaborating and consulting with experts within ERDC, as well as in academia and private industry. Because of time limitations, the numerical models were not calibrated to the field data. The types of data collected included:

  - Tree properties and identification. Tree species and their specific properties (i.e., diameter breast height (DBH) and location) were recorded.

- Root characterization. An integral part of the research was defining the root system. Because of the complexity and variability of a root system even within the same tree species, additional research is needed to better understand the interaction of roots within a soil regime. Two techniques, geophysical and in situ root mapping, were used in the ERDC study. The geophysical technique used most often in previous research to identify a root system is GPR. In addition to GPR, ERDC used electrical resistivity and electromagnetic (EM) induction methods. In situ root mapping includes removing soil surrounding a root system with a high-pressure air lance and then using a handheld digitizer to record the root system. Both the geophysical techniques and in situ root mapping provided geometry of the root system. The test site in Vicksburg, MS, was used to test the applicability of using in situ root mapping to validate the results of the GPR data. Time constraints prevented further validation at other sites.

- Root reinforcement for slope stability. The strengthening effect of root systems was determined by a root pullout apparatus that was used in the field to measure the tensile strength of roots.

- Soil properties for slope stability and seepage. Slope stability is controlled by the strength properties of soil and moisture conditions. Under low-water conditions, soil is partially saturated and significant strength is derived from capillary stresses. When the soil becomes saturated, capillary stresses are absent and strength is controlled by effective confining stresses. With excessive seepage, pore pressures approach or exceed the overburden stress and the shear resistance is lost. When available, existing documents were used for obtaining soil properties of the levee profile. However, to address the effects of roots on hydraulic conductivity and soil moisture, field measurements were taken in a radial pattern extending away from the tree. Measurements in the same pattern were also taken at a nearby site without trees. Hydraulic conductivity was measured using a Guelph Permeameter, and an M300 soil moisture probe was used for recording soil moisture. Additionally, a Troxler nuclear gage was used to measure soil moisture and unit weight of levee and foundation soils in areas containing trees and also in areas devoid of trees. Ideally, root extent would be identified and verified to directly relate any variability in the soil to the tree and its root system.

- **Task 4 – Use numerical model simulation**. Numerical models allow engineers and scientists to evaluate the completeness of their conceptual and mathematical models and to explore sensitivities of individual system components to variations in parameters. In this study, numerical models were used to address the issue of whether the presence of trees affects the stability of levees and/or initiate piping. The presence of woody vegetation also decreases stability by introducing undesirable loads. To make a realistic assessment, the 3-D nature of the problem under critical hydrogeological conditions is taken into account. Numerical model simulations for seepage were performed using three approaches; changes in hydraulic conductivity of a rectangular block representing a tree root system, macroscopic heterogeneity (e.g., assuming a random distribution of hydraulic conductivity), and modeling a defect in a levee blanket from root penetration.

  For both the seepage and slope stability models, critical conditions were identified. Levee performance is gauged by its stability under flood conditions, which in turn is controlled by seepage conditions, by using 2-D seepage and slope stability codes to analyze representative levee cross sections. From these analyses, a relationship between factor of safety and flood level is established. For critical conditions, those nearing failure, the levee was reassessed with differing locations of woody vegetation. From these analyses, the cases in which stability appeared most affected by the woody vegetation were selected for 3-D simulations using a combined seepage-deformation model.

  - **Modeling for sensitivity analysis.** These simulations explore sensitivity of levee performance to changes in the levee and woody vegetation parameters and conditions. These studies used 2-D slices of levee cross sections with properties and loadings that are representative of levees at the selected sites. These simulations permitted varying a much broader range of parameters, including tree position relative to the river stages and material properties of the levee profile. Simulations were done in stages to include no woody vegetation and woody vegetation-modified soil properties. The objective of the analyses without woody vegetation was to define baseline conditions. Transient seepage analyses were used to establish probable critical cases, although the steady-state case was included as the extreme case for the landside region. For the riverside, the r**a**pid-drawdown case was investigated as the critical case.

**Deformation analysis.** High-resolution, 3-D numerical simulations were used to improve the understanding of tree-root effects on levee performance. Three-dimensional seepage analyses represented converging flow fields in and around the root system, and 3-D stability analyses established the extent to which woody vegetation influence stability. The model includes a length of levee sufficient to simulate multiple trees and accommodate a reasonable boundary-condition assignment. Both seepage and stability models were populated from both Federal and non-Federal geotechnical reports. The focus of these studies is on the 3-D effect created by an isolated tree at a specific location. For example, the reinforcing effect of a tree in a 2-D analysis distributed in the implied third dimension will always increase the stability of the slope, especially in the upper few feet where the behavior is approximated by the infinite slope theory. Many results in the literature indicate dramatic increases in stability afforded by the presence of trees. Such stabilizing effects of trees might not be realized in 3-D, where in fact, the presence of trees might not add any stability when the full width of the section is taken into account. A critical limitation to the ERDC research is that a probabilistic system response (fragility curves) was not used to evaluate risk. Therefore, this research should be viewed as an initial study into a complex issue. Future research should include a risk assessment component to accurately relate the findings to anticipated performance of a levee.

# References

Abernethy, B., and I. D. Rutherfurd. 2001. The distribution of riparian tree root in relation to riverbank reinforcement. *Hydrological Processes* 15:63-79.

al Hagrey, S. A. 2007. Geophysical imaging of root-zone, trunk, and moisture heterogeneity. *Journal of Experimental Botany* 58(4):839-854.

Allsop, W., A. Kortenhaus, M. Morris, F. Buijs, R. Hassan, M. Young, N. Doorn, J. van der Meer, P. Van Gelder, M. Dyer, M. Redaelli, M. Utily, P. Visser, R. Bettess, D. Lesniewska, and W. ter Horst. 2007. *Failure mechanisms for flood defence structures*, FLOODsite Project Report T04_06_01. http://www.floodsite.net. (accessed 20 August 2010).

Amato, M., B. Basso, G. Celano, G. Bitella, G. Morelli, and R. Rossi. 2008. In situ detection of tree root distribution and biomass by multielectrode resistivity imaging. *Tree Physiology* 28:1441-1448.

Barthelemy, D., and Y. Caraglio. 2007. Plant architecture: A dynamic, multi-level and comprehensive approach to plant form, structure and ontogeny. *Annals of Botany* 99:375-407.

Barton, C. V. M., and K. D. Montagu. 2004. Detection of tree roots and determination of root diameters by ground penetrating radar under optimal conditions. *Tree Physiology* 24:1323-1331.

Bibalani, G. H., B. Majnonian, E. Adeli, and H. Sanni. 2007. Protection roles of forest and non-forest woody species on slopes in Iran. In Stokes et al. (Eds.) *Eco- and ground bio-engineering: The use of vegetation to improve slope stability,* 73-79, Springer.

Brizendine, A. 1997. Risk based analysis of levees. PhD dissertation, West Virginia University.

Butnor, J. R., J. A. Doolittle, K. H. Johnsen, L. Samuelson, T. Stokes, and L. Kress. 2003. Utility of ground-penetrating radar as a root biomass survey tool in forest systems. *Soil Science Society of America Journal* 67:1607-1615.

Butnor, J. R., J. A. Doolittle, L. Kress, S. Cohen, and K. H. Johnsen. 2001. Use of ground-penetrating radar to study tree roots in the southeastern United States. *Tree Physiology* 21:1269-1278.

Cermak, J., J. Neruda, N. Nadezdina, R. Ulrich, M. Martinkova, R. Gebauer, E. Pokorny, V. Nadezdin, J. Hruska, J. Gasparek, and I. Culek. 2006a. Identification of tree root system damage caused by heavy machinery using new measurement technology suitable for precision forestry. In *Proceedings of the International Precision Forestry Symposium, 1-3 March 2010*, 291-304. South Africa: Stellenbosch University.

Cermak, J., R. Ulrich, Z. Stanek, J. Koller, and L. Aubrecht. 2006b. Electrical measurement of tree root absorbing surfaces by the earth impedance method: 2. Verification based on allometric relationships and root severing experiments. *Tree Physiology* 26:1113-1121.

Chu-Agor, M. L., G. A. Fox, and G. V. Wilson. 2009. Empirical sediment transport function predicting seepage erosion undercutting for cohesive bank failure protection. *Journal of Hydrology* 377:155-164.

Corcoran, M. K., D. H. Gray, D. Biedenharn, C. D. Little, F. Pinkard, P. Bailey, and L. T. Lee. 2011. *Literature review: Vegetation on levees*. ERDC Technical Report (in publication). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Coutts, M. P. 1983. Root architecture and tree stability. *Plant Soil* 71:171-188.

Coutts, M. P. 2004. *Wind and trees*. Cambridge University Press.

Danjon, F., and B. Reubens. 2008. Assessing and analyzing 3-D architecture of woody root systems, a review of methods and applications in tree and soil stability, resource acquisition and allocation. *Plant and Soil* 303:1-34.

Danjon, F., D. H. Barker, M. Drexhage, and A. Stokes. 2007. Using three-dimensional plant root architecture in models of shallow-slope stability. *Annals of Botany* 101(8):1281-1293.

Danjon, F., D. Bert, C. Godin, and H. Stokes. 1999. Structural root architecture of 5-year-old *Pinus pinaster* measured by 3-D digitising and analysed with AMAPmod. *Plant and Soil* 217:49-63.

Danjon, F., T. Fourcaud, and D. Bert. 2005. A root architecture and wind-firmness of mature *Pinus pinaster*. *New Phytologist* 168:387-400.

Di Iorio, A., B. Lasserre, G. S. Scippa, and D. Chiatante. 2005. Root system architecture of *Quercus pubescens* trees growing on different sloping conditions. *Annals of Botany* 95:351-361.

Dupuy, L., T. Fourcaud, and A. Stokes. 2005. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant and Soil* 278:119-134.

Endo, T., and T. Tsuruta. 1969. The effects of tree root upon the shearing strength of soil. Annual Report of the Hokkaido Branch, Tokyo Forest Experiment Station 18:168-179.

Federal Emergency Management Agency (FEMA). 2005. Technical manual for dam owners: Impacts of plants on earthen dams. FEMA 534.

Fourcaud, T., J. N. Ji, Z. Q. Zhang, and A. Stokes. 2008a. Understanding the impact of root morphology on overturning mechanisms: A modeling approach. *Annals of Botany* 101:1267-1280.

Fourcaud, T., X. Zhang, A. Stokes, H. Lambers, and C. Korner. 2008b. Plant growth modeling and applications: The increasing importance of architecture in growth models. *Annals of Botany* 101:1053-1063.

Gartner, H., and C. Denier. 2006. Application of a 3-D laser scaling device to acquire the structure of whole root systems – A pilot study. In *TRACE – Tree Rings in Archaeology, Climatology and Ecology*. Heinrich I., et al. Eds. 4: 288-294.

Godin, C., and Y. Caraglio. 1998. A multiscale model of plant topological structures. *Journal of Theoretical Biology* 191:1-46.

Gray, D. H., and A. T. Leiser. 1982. *Biotechnical slope protection and erosion control*. New York: Van Nostrand Reinhold Company.

Gray, D. H., A. MacDonald, T. Thomann, I. Blatz, and F. D. Shields, Jr. 1991. *The effects of vegetation on the structural integrity of sandy levees*. Technical Report No. REMR-EI-5. Vicksburg, MS: U.S. Army Waterways Experiment Station.

Greenway, D. R. 1987. Vegetation and slope stability. In: *Slope Stability*, M. G. Anderson, and K. S. Richards, eds. Chichester: John Wiley & Sons Ltd.

Hall, J. W., R. J. Dawson, P. B. Sayers, C. Rosu, J. B. Chatterton, and R. Deakin. 2003. *Proceedings of the Institution of Water & Maritime Engineering*, 156(WM3): 235-247.

Hathaway, R. L., and D. Penny. 1975. Root strength in some *populous* and *salix* clones. *New Zealand Journal of Botany* 13:333-344.

Henderson, R., E. D. Ford, and E. Renshaw. 1983. Morphology of the structural root system of Sitka spruce: 1. Analysis and quantitative description. *Forestry* 56:121-135.

Hirano, Y., M. Dannoura, K. Aono, T. Igarashi, M. Ishii, K. Yamase., N. Makita, and Y. Kanazawa. 2008. Limiting factors in the detection of tree roots using ground-penetrating radar. *Plant Soil* 319(1-2):15-24.

Hruska, J., J. Cermak, and S. Sustek. 1999. Mapping tree root systems with ground-penetrating radar. *Tree Physiology* 19:125-130.

JESCO Environmental & Geotechnical Services, Inc. 2008. *Documentation and analysis of tree root extent and behavior along and in levees and floodwalls in the New Orleans District*. Final Report. New Orleans District: U.S. Army Corps of Engineers.

Kaestner, A., M. Schneebeli, and F. Graf. 2006. Visualizing three-dimensional root networks using computed tomography. *Geoderma* 136:459-469.

Lambe, T. W., and R. V. Whitman. 1969. *Soil mechanics*. New York: Wiley.

Milliken, and Bledsoe. 1999. Biomass and distribution of fine and coarse roots from blue oak (*Quercus douglasii*) trees in the northern Sierra Nevada foothills of California. *Plant and Soil* 214:27-38.

Morelli, G. F., T. Zenone, M. Teobaldelli, F. Fischanger, M. Matteucci, and G. Seufert. 2007. Use of Ground-Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) to study tree roots volume in pine forest and poplar plantation. In *Proceedings of the 5$^{th}$ International Workshop on Functional-Structural Plant Models,* ed. Prusinkiewicz, Hanan, and Lane, 21:1-4. New Zealand: Napier.

Nadezhdina, N., and J. Cermak. 2003. Instrumental methods for studies of structure and function of root systems of large trees. *Journal of Experimental Botany* 54(387):1511-1521.

Norris, J. E. 2005. Root mechanics applied to slope stability. PhD thesis, Nottingham Trent University, Nottingham, UK.

Norris, J. E., and J. R. Greenwood. 2000. In situ shear and pull out testing to demonstrate the enhanced shear strength of root reinforced soil. In: *Proceedings of the 8th International Symposium on Landslides, Cardiff, 26-30 June 2000*. Thomas Telford, London, 593-597.

Norris, J. E., and J. R. Greenwood. 2003. In situ shear box and root pull-out apparatus for measuring the reinforcing effects of vegetation. *Field Measurements in Geomechanics*: *Proceedings of the 6th International Symposium. Oslo, Norway, 23–26 September 2003*. F. Myrvoll, ed., Oslo. Swets and Zeitlinger, Lisse, 593-597.

Norris, J. E., A. Stokes, S. B. Mickovski, E. Cammeraat, R. van Beek, B. C. Nicoll, and A. Achim. 2007. *Slope stability and erosion control: Ecotechnological solutions*. Dordrecht, Holland: Springer.

Pollen, N., and A. Simon. 2004. Estimating the mechanical effects of riparian vegetation on stream bank stability using fiber bundle model. *Water Resource Research* 41: 1-11.

Pollen-Bankhead, N., and A. Simon. 2009. Enhanced application of root-reinforcement algorithms for bank-stability modeling. *Earth Surface Processes and Landforms* 34:471-480.

Pradal, C., S. Dufour-Kowalski, F. Boudon, and N. Dones. 2007. The architecture of OpenAlea: A visual programming and component based software for plant modeling. *5th International Workshop on Functional-Structural Plant Models, 4-9 November 2007, Napier, New Zealand.*

Read, J., and A. Stokes. 2006. Plant biomechanics in an ecological context. *American Journal of Botany* 93(10):1546-1565.

Retzlaff, W. A., J. A. Handest, D. M. O'Malley, S. E. McKeand, and M. A. Topa. 2001. Whole-tree biomass and carbon allocation of juvenile trees of loblolly pine (*Pinus taeda*): Influence of genetics and fertilization. NRC Canada, *Canadian Journal of Forest Research* 31:960-970.

Reubens, B., J. Poesen, F. Danjon, G. Geudens, and B. Muys. 2007. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: A review. *Trees* 21:385-402.

Riestenberg, M., and S. Sovonick-Dunford. 1983. The role of woody vegetation in stabilizing slopes in the Cincinnati, Ohio, area. *GSA Bulletin* 94(4):506-518.

Schaefer, J. A., T. M. O'Leary, N. D. Vroman, R. Fell, M. Foster, J. Cyganiewicz, G. Sills, and R. Davidson. 2010. *Internal erosion toolbox: A method for estimating probabilities of failure of embankment dams due to internal erosion, best practices guidance document*. Final draft, U.S. Army Corps of Engineers.

Shields, F. D., A. MacDonald, and H. H. Pahl III. 1989. Vegetation on riprap revetment-Problem definition and study approach. In *Proceedings of the Sixteenth Annual Conference of Water Resources Planning and Management, Sacramento, CA, 21-25 May 1989*.

Shields, F. D. Jr., L. T. Ethridge, and T. N. Waller. 1990. A study of vegetation on revetments, Sacramento Riverbank protection project. Phase 1, WES Literature Review and Pilot Study.

Shields, F. D., and D. H. Gray. 1992. Effects of woody vegetation on sandy levee integrity. *Water Resources Bulletin* 28(5):917-931.

Sills, G., L. F. Harder, T. Wolff, M. Al-Hussaini, C. Groves, and M. Duncan. 2003. Recommendations for seepage design criteria, evaluation and design practices, 2003 CESPK Levee Task Force, Report prepared for the Sacramento District U.S. Army Corps of Engineers, 93 p.

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: Upper Truckee River, California. *Journal of the American Water Resources Association* 42:99-114.

Steenbergen, H.M.G.M., B. L. Lassing, A. C. W. M. Vrouwenvelder, and P. H. Waarts. 2004. Reliability analysis of flood defence systems. *HERON* 49(1):51-73.

Stoeckler, J. H., and W. A. Kluender. 1938. The hydraulic method of excavating the root systems of plants. *Ecology* 19(3):355-369.

Stokes, A. 1999. Strain distribution during anchorage failure in root systems of maritime pine (*Pinus pinaster* Ait.) at different ages and tree growth response to wind-induced root movement. *Plant Soil* 217:17-27.

Ter Horst, W. L., S. N. Jonkman, and J. K. Vriling. 2006. Probabilistic analysis of safety of dikes during flood waves, In *Safety and reliability for managing risk*. C. Guedes Soares & E. Zio (ed.), London: Taylor & Francis.

Tharp, B. C., and C. H. Muller. 1940. A rapid method for excavating root systems of native plants. *Ecology* 21(3):347-350.

Tosi, M. 2007. Root tensile strength relationships and their slope stability implications of three shrub species in Northern Apennies (Italy). *Geomorphology* 87:268-283.

U.S. Army Corps of Engineers. 1956. *Investigation of underseepage and its control, Lower Mississippi River Levees.* Technical Memorandum No. TM-3-424, 2 volumes. Vicksburg, MS: U.S. Army Engineer, Waterways Experiment Station.

———. 1971. *Landscape planting adjacent to floodwalls, levees and dam embankments*. ETL 1110-2-113, DAEN: CWE-M, U.S. Army, Office of the Chief of Engineers.

———. 1972. *Guidelines for landscape planting and vegetation management at floodwalls, levees, and embankment dams*. Engineer Manual (EM) 1110-2-301. Washington, DC.

U.S. Army Corps of Engineers. 1988a. *Vegetation and the structural integrity of levees: Results of field investigations*. Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Technical Note (TN) EI-M-1.3. Washington, DC.

———. 1988b. *Issues regarding vegetation management on levee embankments*. REMR Technical Note (TN) EI-M-1.4. Washington, DC.

———. 1993. *Guidelines for landscape planting and vegetation management at floodwalls, levees, and embankment dams*. Engineer Manual (EM) 1110-2-301. Washington, DC.

———. 1999. *Evaluating the reliability of existing levees, Appendix B in risk-based analysis in geotechnical engineering for support of planning studies*. Engineering Technical Letter (ETL) 1110-2-556, 28 May, Washington, DC.

———. 2000a. *Guidelines for landscape planting and vegetation management at floodwalls, levees, and embankment dams*. Engineer Manual (EM) 1110-2-301. Washington, DC.

———. 2000b. *Design and construction of levees*. Engineer Manual (EM) 1110-2-1913. Washington, DC.

———. 2009. *Guidelines for landscape planting and vegetation management at levees, floodwalls, embankment dams, and appurtenant structures*. Engineer Technical Letter (ETL) 1110-2-571. Washington, DC.

Vorogushyn, S., B. Merz, and H. Apel. 2009. Development of dike fragility curves for piping and micro-instability breach mechanisms. *Natural Hazards and Earth System Sciences* 9(2009):1383-1401.

Vrouwenvelder, A.C.W.M. 1987. *Probabilistic design of flood defenses*. Report B-87-404. IBBC-TNO (Institute for Building Materials and Structures of the Netherlands, Organization of Applied Scientific Research). The Netherlands.

Waldron, L. J. 1977. The shear resistance of root-permeated homogeneous and stratified soil. *Soil Science Society of America Journal* 41:843-849.

Watson, A. J., C. J. Phillips, and M. Marden. 1999. Root strength, growth, and rates of decay: root reinforcement changes of two tree species and their contribution to slope stability. *Plant Soil* 217: 39-47.

Wu, T. H. 1976. Investigation of landslides on Prince of Wales Island, Alaska, Geotechnical Engineering Report No. 5. Columbus, OH: Ohio State University.

# 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**
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.

**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, levee, or dam 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 with a typical grain size less than 0.004 mm. Possesses electromagnetic properties which bind the grains together to give a bulk strength or 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, by the action of wind and water.

**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. 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 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 interpreting signals received simultaneously from several of a constellation of special satellites.

**Gradient**
A measure of slope (soil- or water-surface) in meters of rise or fall per meter of 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 which 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 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.

**Headwaters**
A continuous graph showing the properties of stream flow with respect to time.

**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.

**Hydraulic Gradient**
The change in total head with a change in distance in a given direction which yields a maximum rate of decrease in head.

# I

**Infiltration**
Water entering the groundwater system throughout the land surface.

# J K

# L

**Levee**
An embankment raised along a river to protect adjoining lands from inundation.

**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 that is the mean of hourly water elevations observed over a specific 19-year metonic cycle (the National Tidal Datum Epoch). The abbreviation amsl refers to annual mean sea level.

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

# N

**Natural Levee**
A natural embankment that parallels the course of a river. A natural levee is built up over time by sediment deposition associated with seasonal flooding.

# 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, $= Vv/VT \times 100$.

# 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 sea floor. (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 geologic usage, 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 referring 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

[1]The definitions in this glossary are from the following references:

U.S. Army Corps of Engineers. 1987. *Reservoir Water Quality Analyses*. Engineer Manual (EM) 1110-2-1201. Washington, DC.

U.S. Army Corps of Engineers. 1993. *River Hydraulics*. Engineer Manual (EM) 1110-2-1416. Washington, DC.

U.S. Army Corps of Engineers. 1995. *Geophysical Exploration for Engineering and Environmental Investigations*. Engineer Manual (EM) 1110-1-1802. Washington, DC.

U.S. Army Corps of Engineers. 1999. *Groundwater Hydrology*. Engineer Manual (EM) 1110-2-1421. Washington, DC.U.S. Army Corps of Engineers. 2002. *Photogrammetric Mapping*. Engineer Manual (EM) 1110-1-1000. Washington, DC.

U.S. Army Corps of Engineers. 2001. *Emergency Employment of Army and Other Resources Civil Emergency Management Program*. Engineer Regulations (ER)500-1-1. Washington, DC.

U.S. Army Corps of Engineers. 2002. *Hydrographic Surveying*. Engineer Manual (EM) 1110-2-1003. Washington, DC.

U.S. Army Corps of Engineers. 2003. *Coastal Engineering Manual - Appendix A - Glossary of Coastal Terminology*. Engineer Manual (EM) 1110-2-1100. Washington, DC.

U.S. Army Corps of Engineers. 2007. *Engineering and Design: Control and Topographic Surveying*. Engineer Manual (EM) 1110-1-1005. Washington, DC.

U.S. Army Corps of Engineers. 2011. *NAVSTAR Global Positioning System Surveying*. Engineer Manual (EM) 1110-1-1003. Washington, DC.