Synthesis of Levee Vegetation Research Results (2007–2014)

Prepared for:

California Levee Vegetation Research Program

Prepared by:

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cbec eco engineering

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In 2009, the California Department of Water Resources (DWR) and the Sacramento Area Flood Control Agency (SAFCA) partnered with policy makers, levee managers, and researchers from a number of local, State, and federal agencies to establish the California Levee Vegetation Research Program (CLVRP). The CLVRP was established to (1) support original scientific research about vegetation and its impacts on levees and (2) provide a science-based foundation to develop levee vegetation management policies and maintenance procedures.

The CLVRP supports research in a collaborative environment that builds upon existing knowledge about vegetation and its impacts on levees. Participating agencies include the National Marine Fisheries Service, U.S. Fish and Wildlife Service, DWR, California Department of Fish and Wildlife, Central Valley Flood Protection Board, SAFCA, and Central Valley reclamation districts. Funding and project management for Phase I of the CLVRP were provided primarily by DWR and SAFCA. Phase I of the CLVRP resulted in completed research on several topics, which is reviewed in this Levee Vegetation Synthesis Report. Phase II of the CLVRP is continuing and is supporting further research.

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- Vertical photo on left: Sacramento River south of downtown Sacramento. Photo taken by AECOM.

- Top horizontal photo: Sacramento River, Maintenance Area 9, Big Pocket area. Photo taken by F. Douglas Shields, Jr. (synthesis report author).

- Bottom photo, far left: Sacramento River, Natomas Levee Improvement Project near the Sacramento/Sutter County line. Photo taken by F. Douglas Shields, Jr. (synthesis report author).

- Bottom photo, second from left: Pocket Area (Site G), Sacramento River east levee, Sacramento. Photo taken by University of California, Davis team/Alison Berry.

- Bottom photo, second from right: Cal Expo stump seepage site, north levee of American River, Sacramento. Photo taken by University of California, Berkeley team/Michelle Shriro/Diego Cobos-Roa.

- Bottom photo, far right: Sacramento River, Maintenance Area 4, near Sacramento Maintenance Yard. Photo taken by F. Douglas Shields, Jr. (synthesis report author).

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Acronyms and Other Abbreviations

µm	micrometer(s)
2014 WRRDA	2014 Water Resources Reform and Development Act
2D	two-dimensional
3D	three-dimensional
ASCE	American Society of Civil Engineers
BSTEM	Bank Stability and Toe Erosion Model
CFR	Code of Federal Regulations
CIRIA	Construction Industry Research and Information Association
CLVRP	California Levee Vegetation Research Program
cm	centimeter(s)
CVFPP	Central Valley Flood Protection Plan
dbh	diameter at breast height
deg	degrees
Delta	Sacramento–San Joaquin Delta
DRMS	Delta Risk Management Strategy
DWR	California Department of Water Resources
ERDC	Engineer Research and Development Center
ERDC Program	U.S. Army Corps of Engineers Engineer Research and Development Center levee vegetation program
FBM	fiber bundle model
FEMA	Federal Emergency Management Agency
FORM	First-Order Reliability Method
FOSM	First-Order Second Moment
Fs	factor of safety
ft	foot, feet
ft/ft	feet per foot
ft/s	feet per second
g/cm^3	grams per cubic centimeter
GIS	geographic information system
GPR	ground-penetrating radar
in	inch(es)
K_b	bulk hydraulic conductivity
kg	kilogram(s)

km	kilometer(s)
kPa	kilopascals
LCM	Life Cycle Management
LiDAR	Light Detection and Ranging
LVMS	Levee Vegetation Management Strategy
m	meter(s)
m/s	meter(s) per second
m^2	square meter(s)
M_{crit}	critical moment for overturning
mm	millimeter(s)
MPa	megapascal(s)
mph	mile(s) per hour
N/A	not applicable
Nm	newton meter(s)
psf	pounds per square foot
PL	Public Law
RAR	root-area ratio
SA	Secretary of the Army
SAFCA	Sacramento Area Flood Control Agency
SPFC	State Plan of Flood Control
T-LiDAR	Terrestrial Light Detection and Ranging
ULDC	California Urban Levee Design Criteria
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
VFZ	vegetation-free zone

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1 Introduction

Abstract
Levee managers have raised many questions in connection with practices and policies for managing vegetation on and adjacent to levee embankments. The primary interests of levee managers center upon flood risk management and structural reliability, of course, but their interests also extend to ecological resources; aesthetics; burrowing mammals; tree root architecture; and procedures for detecting, mapping, and modeling tree roots and their interaction with geotechnical properties of soils. Most of these topics have been studied under major research programs conducted under the aegis of the State of California, the U.S. Army Corps of Engineers Engineer Research and Development Center, and universities in France and Austria. This report aims to synthesize much of the work published subsequent to the first Levee Vegetation Research Symposium, held in 2007. Besides summarizing and synthesizing recently published findings, a key objective is to identify remaining points of scientific debate and data gaps, and to describe the author's interpretation of the implications of new research for consideration by levee managers and policy-makers.

1.1 Purpose and Context

This technical report was commissioned by the California Department of Water Resources (DWR) to provide an objective description and synthesis of research pertaining to woody vegetation on levees, with particular emphasis on U.S. and international research published between 2007 and 2014. This research has important application across the U.S. and internationally, because management of vegetation on levees is a controversial subject that had undergone little study before the research described in this report.

Researchers typically vary in their approaches to selecting and interpreting research findings regarding controversial topics. However, DWR commissioned this report mainly to provide policy-makers, levee managers, and other interested parties with an impartial presentation of recently published findings, points of remaining scientific debate, identification of data gaps, and an informed expert's synthesis of "what it all means." The sections of this report are written as an objective presentation of the research and scientific dialog, with three exceptions:

- In the "Points of Scientific Debate" section of each chapter, after describing the debate, the author may weigh in with his judgment if he finds that one or more researchers have developed significantly more credible or compelling evidence.

- In the "Implications" section of each chapter, the author provides his own informed judgment regarding the key issues for levee managers and policy-makers to consider and his interpretation of trends or the weight of scientific evidence that may inform their actions and decisions.

- Chapter 15, “Summary and Conclusions,” draws heavily on many of the chapter sections dealing with scientific debate and potential implications.

Because the report’s funding comes from DWR, the report focuses on issues and research that have important implications for management of California’s extensive system of levees that provide flood control, water supply, ecological, and other benefits. In particular, DWR has expressed that its fundamental interest and most critical need is to understand how best to manage existing woody vegetation that has grown over many decades, in some cases extensively, on California’s hundreds of miles of “legacy” levees.

Chapter 4 of California’s 2012 Central Valley Flood Protection Plan (CVFPP) describes several categories of woody vegetation on levees that “will not be removed (unless changed conditions cause such vegetation to pose an unacceptable threat or it creates a visibility problem within the vegetation management zone)” (DWR 2012a:4-13 through 4-15). Selective management of vegetation on levees is also a policy consideration outside the U.S. Therefore, the “Implications” section of each chapter in this report often discusses the implications of the research, and the author’s advice based on the weight of evidence, for selectively managing existing woody vegetation to reduce risk and uncertainty.

The Central Valley of California has a long history of struggling with flooding, and levees are a key component of the flood risk management system (James and Singer 2008). The valley is prone to flooding as a result of climatic and topographic factors that were exacerbated by sediment deposition in river channels following 19th century hydraulic mining in the Sierra Nevada. Devastating floods triggered construction, beginning in 1850, of the existing flood protection system. Initial work in the 19th century was limited to only portions of the levee system; however, 20th century construction resulted in the present system, which includes 10 multipurpose reservoirs in upper parts of the watershed and levees and bypass channels along major rivers. The State is actively planning for future flood events and the Central Valley Flood Protection Board has adopted the 2012 CVFPP (DWR 2012a). The CVFPP and its companion Conservation Framework describe the State of California’s approach to managing levee vegetation. A 5-year update of the CVFPP is due in 2017, which provides an opportunity for State policy to incorporate new science.

Management of woody vegetation (trees and large shrubs) on levees is an important component of the CVFPP (DWR 2012a). However, management of woody vegetation on earthen flood-control levees is controversial. Traditional engineering standards and historical federal standards in the U.S. have prohibited or limited woody vegetation on levees because of concerns—based in part on precaution in the face of uncertainty—that such vegetation may create problems such as inducing seepage along roots or voids created by decaying roots or stumps, holes created by windthrown or water-thrown trees, slope instability caused by the weight of trees, and obstruction of inspection and flood fighting (Gray et al. 1991). Despite the standards, woody vegetation has been allowed to grow and mature, and now is in conflict with the standards. Many levees in California support significant amounts of woody vegetation that represent a final vestige of once-vast riparian woodlands. This vegetation provides habitats for several threatened

and endangered species. Further, the vegetation is valued for aesthetic reasons and may contribute to levee stability and durability.

Concern for levee safety and reliability spiked upward following structural failures of floodwalls and some levees in New Orleans associated with Hurricane Katrina in 2005, triggering debate about the national problem of inadequate flood risk management infrastructure (Galloway 2008). After Hurricane Katrina, U.S. federal policy regarding all aspects of levee design and construction was carefully reviewed by the U.S. Army Corps of Engineers (USACE). USACE Headquarters chose to take a more conservative approach to levee risk management, and its formulation and interpretation of federal policy regarding levee vegetation became more restrictive. With the issuance of interim vegetation guidelines (June 2007) and final policy (April 2009), USACE called for the removal of existing trees from levees nationwide under a nationally uniform standard. Draft guidelines for obtaining variances from this policy, which were circulated for review via the *Federal Register* in 2010 and 2012, were much more restrictive than previous guidelines. This USACE national levee vegetation policy has been controversial and is currently being reconsidered as directed by the 2014 Water Resources Reform and Development Act (2014 WRRDA). This reconsideration offers the opportunity for U.S. national policy to consider and incorporate new science. It is hoped that this report will prove useful and constructive in that process.

Just as Hurricane Katrina reinvigorated flood risk management at the federal level, it did so in California. Voters soon approved propositions providing billions of dollars for flood system improvements. Major flood legislation was enacted in 2007, renaming the State Reclamation Board the Central Valley Flood Protection Board, establishing protection from 200-year flood events as the State's urban standard, directing the preparation of the CVFPP (DWR 2012a) and 5-year updates, and more closely linking development and flood risk management, among other things (DWR 2007). Policy for management of levee vegetation is just one component of an overall risk management strategy for California levees in the CVFPP.

Following a major symposium in 2007 (Sacramento Area Flood Control Agency [SAFCA] n.d.), a consortium of State and local agencies funded a multidisciplinary research program, the California Levee Vegetation Research Program (CLVRP). Several projects composing that program are complete or nearing completion.

Almost simultaneously, the USACE Engineer Research and Development Center (ERDC) initiated a national research program on the effects of levee vegetation, culminating with a final report published in 2011 (Corcoran et al. 2011). Some follow-on work funded by USACE continued after 2011. In addition, scientists in Europe, principally France and Germany, have been at work on similar issues (e.g., Zanetti 2010, Gianetta et al. 2013). This document seeks to summarize and synthesize recent findings by these and other researchers that are relevant to the levee vegetation issue. Use of research findings may reduce uncertainty associated with the impacts of vegetation on flood-control levees.

1.2 Definition and Description of Levees

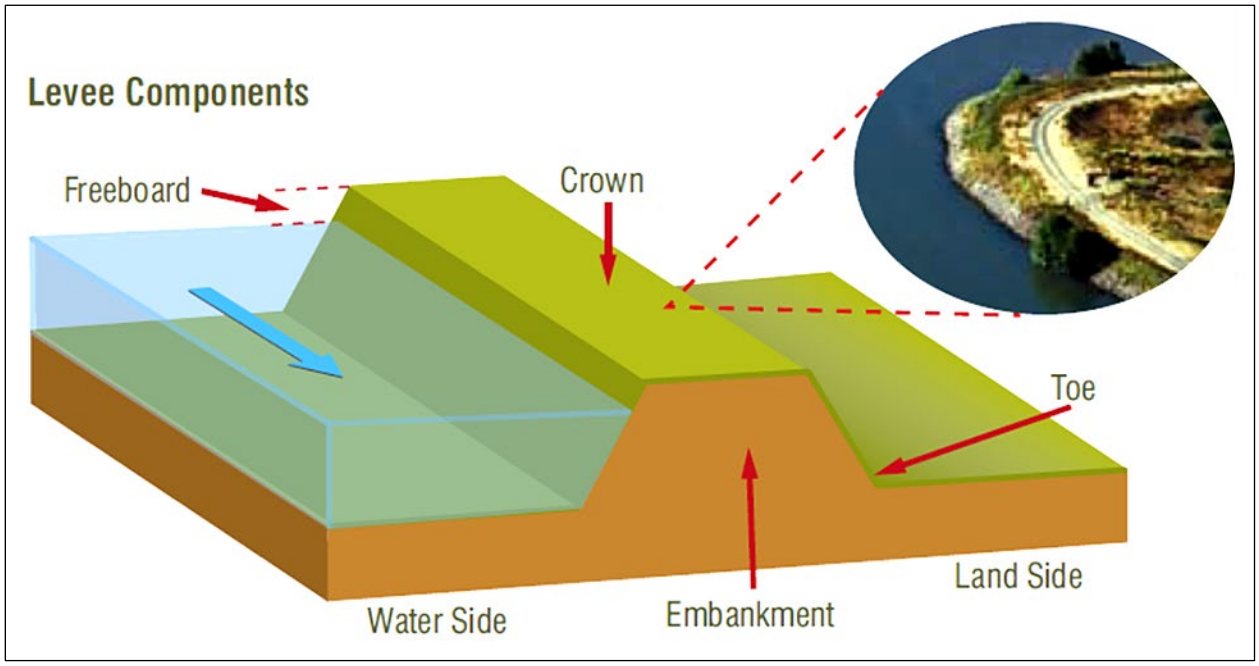
A levee is a manmade earthen embankment that provides flood protection from temporary high water (Shields and Palermo 1982, Federal Emergency Management Agency [FEMA] 2008). Embankments that are constructed to impound permanent reservoirs or protect coastal areas from hurricane surges or that are subjected to continuous hydraulic loads are not addressed in this synthesis. Levees usually lie parallel to and on either side of a channel, or they encircle a protected area. Levees help to protect against rising floodwaters by confining the water to a deeper floodway. The majority of levees in the United States are public works projects that are part of a flood-control protection plan. Levees are often constructed from material obtained from the riverside, and the land in between the levees is called the floodway, batture, or foreshore. A levee is typically less engineered than an earthen dam because levees are only designed to hold hydraulic loading for less than a few weeks per year. Levees in California tend to be smaller (in cross section) and older than earthen dams. Standards of design, foundation conditions, and maintenance practices often vary along a levee system (Construction Industry Research and Information Association [CIRIA] 2013). A typical levee section is composed of several parts including the embankment crown, slopes, and toes (Figure 1-1). Levee design usually includes consideration of foundation conditions—the floodplain soils underlying the embankment and adjacent areas—and may include provisions for modifying foundation conditions.

There are about 100,000 miles of levees in the U.S., with an approximate average age of 54 years (National Committee on Levee Safety 2011). Levees are found in approximately 22% of the nation's counties and in all 50 states, and about one-third of all communities larger than 50,000 people have some levee protection. About half of communities larger than 1 million have some levee protection. The vast majority of levees in the U.S. are not part of any federal program. Approximately 15% of levees (by length) in the U.S. are operated by USACE. Most of these levees are mapped and listed within the National Levee Database (USACE n.d.).

1.3 Levee Maintenance

Levees tend to deteriorate over time if they are not carefully maintained. Because levees are long, linear structures that are part of a system, the adage "a chain is only as strong as its weakest link" is particularly apt (CIRIA 2013). Levee maintenance includes removal of vegetation (mowing or burning), replanting, and management of desirable vegetation. Maintenance also requires the control of unwanted animals, filling of animal burrows, and repair of damaged areas. Damage may occur due to erosion by wave wash or currents, underseepage, through-seepage, animal burrows, ruts, foot traffic by animals or humans, and slips or slides (Hynson et al. 1985).

Additional maintenance actions involve upkeep of access roads and ramps, appurtenant structures such as flood gates and pumping stations, and stockpiles of emergency construction materials.



Source: ASCE 2010 (permission requested).

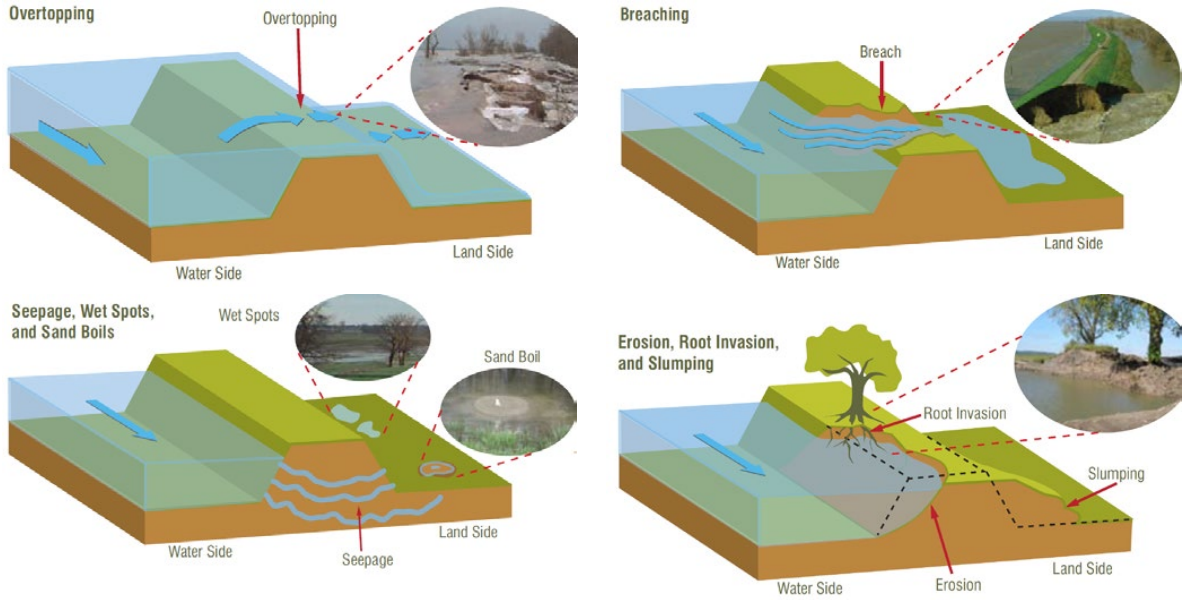
Figure 1-1. Levee Components

1.4 Levee Failure

Levee failure often occurs without warning during high-water periods. Observed failure mechanisms include overtopping, breaching, seepage, and slumping (slope instability) (American Society of Civil Engineers [ASCE] 2010) (Figure 1-2).

Overtopping means that the water passes over the top of the levee, often causing erosion that eventually breaches the levee. Seepage occurs through or under the levee and can create structural failure. When through-seepage triggers subsurface internal erosion, continuous voids or "pipes" may form within the levee and progressively enlarge until the levee washes out completely. Initiation of through-seepage is often associated with cracks or macropores (holes or cavities larger than about 0.08 millimeter [mm]). It is worth noting at this point that preexisting cracks, fractures, or macropores are not necessary to initiate seepage failures in earthen dams and embankments (Sherard 1986). Seepage-related failures may be triggered by hydraulic fracturing[1] or by seepage that results in selective removal of fines by piping in gap-graded soil fills.

[1] Hydraulic fracturing is a tensile separation along an internal surface in an earthen embankment or dam that is facilitated by differential settlement and internal stress transfer. The effective stress on this surface approaches zero; that is, the neutral or pore water pressure equals the total vertical-confining stress. Such surfaces become the locus for fractures that are jacked open during hydraulic loading. Low, homogeneous embankments without internal filters or drains like levees are particularly susceptible.



Source: ASCE 2010 (permission requested).

Figure 1-2. Four Levee Failure Modes Posed by ASCE

Underseepage is a threat to levee integrity caused by the emergence of water on the landward side and is often manifested by localized upwellings or seeps that can result in sand boils. Sand boils occur when groundwater has enough pressure to well up through a bed of sand. The water looks like it is "boiling" up from the bed of sand, hence the name. Sand boils can create conditions known as soil liquefaction, in which soils become fluid and levee failure can be very rapid. Seepage erosion is often progressive, and thus is more hazardous as the duration of hydraulic loading increases. Slope instability is surface slumping or collapse that is often associated with seepage patterns that cause pressure in the embankment. Levee failure processes often act in a synergistic fashion. For example, seepage may cause slope failure that lowers the levee crest enough to allow overtopping. Erosion caused by overtopping can then create a breach.

1.5 Levee Vegetation

1.5.1 Standards

Most levee projects in the United States are constructed and maintained by nonfederal (private or local) interests. The National Committee on Levee Safety (2011) estimates that there may be more than 100,000 miles of levees in the U.S. However, a small but important percentage of levees (perhaps 10%) either are maintained by federal government agencies or must meet federal maintenance guidelines to qualify for critical emergency assistance in repairing or restoring levees to pre-disaster conditions if they are damaged by a flood event (USACE 2001). This assistance program is known as the "Public Law (PL) 84-99 program," after the authorizing legislation.

Historically, federal standards have called for levee embankment vegetation to be limited to dense, sod-forming grass 2–12 inches (in) high (33 Code of Federal Regulations [CFR] 208.10, USACE 1968 in Hynson et al. 1985) and to be substantially free of weeds and bare spots (USACE 2009a, 2014a). Nolan (1984) presents a historically interesting overview of federal policy as applied to the Central Valley of California. Regulations stipulate that no condition is allowed that impairs levee inspection, maintenance, or flood-fighting capabilities, or that restricts the passage of flood flows. Landscape plantings (i.e., trees and shrubs) could be placed on levee embankments for recreational or aesthetic reasons, but only if barriers or overbuilt sections were used to ensure that roots did not penetrate a designated root-free zone that corresponded to the basic levee prism (USACE 1972 in Hynson et al. 1985, Nunnally et al. 1987). To this end, a 3-foot (ft) buffer zone was required between the deepest expected penetration of roots and the basic levee structure (Gray et al. 1991).

Regional variances to these vegetation standards were permitted, especially where the climate did not permit growth of sod-forming grass. For example, USACE (1955, in USACE 2010a) allowed for retention of brush and small trees on the waterward slope of Sacramento River Flood Control Project levees, where desirable, to prevent erosion and wave wash. Additional provisions for retaining existing vegetation are found in supplemental operation and maintenance manuals for specific flood-control units (USACE 2010a).

Historically, exceptions to this vegetation standard were permitted under a variance process. Regular removal of debris and repair of erosion is also required. The law requires that levees be inspected before the beginning of flood season, immediately after each major high-water event, and continuously during flood periods. The time between inspections is not to exceed 90 days. Levees must meet federal standards to remain active in the PL 84-99 rehabilitation and inspection program (under Engineer Regulation 500-1-1). In addition to PL 84-99, USACE levee vegetation standards affect vegetation management directly, indirectly, or potentially through:

(1) issuance of permits (408 permit) for levee modifications funded by nonfederal entities;

(2) levee modification by nonfederal entities using federal funds supplied by USACE, which requires a USACE engineering report and congressional authorization; and

(3) USACE accreditation of levees under provisions of the National Flood Insurance Program when a local entity requests such accreditation from USACE.

1.5.2 Controversy Associated with Levee Vegetation

Vegetation larger than sod-forming grass on levees occurs frequently on California levees. Advocates for selective retention of levee vegetation and advocates for vegetation removal have made a number of assumptions regarding the interactions between vegetation, levees, high-water events, and other factors. Research described in this report may be used to evaluate assumptions related to levee vegetation that inform policy and management decisions. As noted above, benefits ascribed to such vegetation include habitat and aesthetic values, enhancement of levee

stability, and erosion protection. Objections to woody vegetation on levees stems from the following concerns, which have a range of evidentiary support[2]:

- Aboveground portions of woody plants might obscure visual inspection and obstruct access for maintenance and flood fighting.
- Vegetation might facilitate through-seepage by creating macropores associated with living and dead roots.
- Vegetation might negatively affect slope stability as a result of potential impacts associated with the weight of the vegetation, wind action on the upper parts of the vegetation, and enhanced seepage and infiltration.
- Trees are subject to windthrow, which might create voids (pits) in the levee prism that might result in additional risk to levee integrity.
- Trees and shrubs might attract burrowing animals and make them more difficult to control.
- Scour around erect or fallen trees might produce erosion during high flows.
- Tree roots might uplift hardscapes such as paved or interlocking revetments, drainages, or gate structures.
- Trees might adversely affect desirable vegetation such as grasses by either creating shade or changing the chemical nature of the soil.

1.6 Recent Research

This report aims to provide a synthesis of recently completed research on topics germane to management of vegetation on and adjacent to levee embankments. There are at least three major sources of recent findings: USACE, the CLVRP, and projects in France and Austria. This synthesis seeks to fully exploit these findings, but helpful information from other sources is also assessed and included. Additional detailed information about each program's studies and results is embedded as appropriate in Chapters 2–14 of this report.

1.6.1 USACE Engineer Research and Development Center

The report for the USACE ERDC levee vegetation program (ERDC Program) by Corcoran et al. (2011) was preceded by a literature review in 2007 that produced a large, annotated

[2] It can be difficult to determine the role of vegetation in levee stability or failure in the event of a breach because physical evidence is often washed away or altered during the high-water event. The observed presence of roots in a breached section of a levee is not conclusive, as causation cannot be inferred. It is as logical to infer that the roots reinforced the embankment and helped delay or limit the extent of the breach or failure as it is to infer that they facilitated it.

bibliography. The ERDC Program was conducted over 18–20 months or less and included field data collections and numerical modeling. The ERDC Program was "not intended to weigh positive versus negative effects of woody vegetation on levees." The positive and negative impacts of woody vegetation on two key failure modes (deep-seated slope instability and initiation of seepage erosion) were examined under a variety of modeled conditions.

Qualitative assessments were conducted at six sites east of or within Dallas, Texas. Five of the six were levee projects while the sixth considered selected trees near Vicksburg, Mississippi. More detailed field data (or "site characterizations") were collected at four sandy levees in the western U.S. The field data collections included compilation of geological and geotechnical data for levees and foundation conditions from existing publications, sampling and study of levee soil properties, tree root properties (tensile strength and spatial distribution), and levee geometry. Several technologies for noninvasive detection and mapping of tree roots were examined. Numerical simulations of levee seepage and slope stability were developed to represent typical conditions at the "site characterization" levees. Modeling included two-dimensional (2D) analyses of the four characterization sites and three-dimensional (3D) simulations representing two of these sites (Tracy and Corcoran 2012). Model input included only the root strength from the field data collections, as much of the numerical modeling was concurrent with field data collection. The ERDC Program was thoroughly documented in a four-volume technical report (Corcoran et al. 2011) and summarized by Corcoran (2012).

1.6.2 California Levee Vegetation Research Program

Simultaneously with the initiation of the USACE research program, the California Roundtable for Central Valley Flood Management (formerly the California Levees Roundtable) formed the CLVRP to complement the ERDC studies. Phase 1 of this effort involved a range of topics including associations between vegetation and burrowing animals on levees; levee tree root architecture; seepage through levees with live trees, dead stumps, and herbaceous cover; effects of tree roots on levee slope stability; computer modeling to simulate levee seepage and slope stability; forces required to overturn trees (windthrow); and spatial distributions of roots in the vicinity of levee slurry cutoff walls. Fieldwork occurred on selected levees in the Central Valley of California. An additional component examined records of levee damage and failure incidents in light of records of woody vegetation growing at the incident sites.

Phase 1 end products, exclusive of conference proceedings and journal papers, are listed in Table 1-1. Many of these reports were not available in time for use in this synthesis (July 2013–July 2014), but preliminary products and personal communications with authors and principal investigators were used in cases where final reports were not available. Phase 2, a more tightly focused set of studies, continues as of this writing.

1.6.3 Europe

France

A multifaceted research program dealing with the effects of trees growing on dikes along French waterways was conducted at France's National Research Institute of Science and Technology for Environment and Agriculture. This work was performed primarily by a team led by a Ph.D.

Table 1-1. Reports from Phase 1 of the California Levee Vegetation Research Program

Report Title	Citation
Habitat Associations of Burrowing Mammals along Levees in the Sacramento Valley, California	Van Vuren and Ordenaña (2011)
Influence of Adjacent Crop Type on Occurrence of California Ground Squirrels along Levees in the Sacramento Valley, California	Van Vuren et al. (2013)
Burrow Dimensions of Ground Squirrels, with Special Reference to the California Ground Squirrel	Van Vuren and Ordenaña (2012)
Investigation of Tree Root Penetration into A Levee Soil-Cement-Bentonite Slurry Cutoff Wall	Harder et al. (2010)
Investigation of Tree Root Penetration into a Levee Soil-Cement-Bentonite Slurry Cutoff Wall—Part II	Harder et al. (2011)
Windthrow Potential on Levees: Stability of Two Species of Central Valley Trees on River Levees, Evaluation by Static Winching Tests	Peterson and Claassen (2012)
Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 1—Review of Literature and Case Histories	Cobos-Roa et al. (2014a)
Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 2—Parallel Trench Wetting Front Test, North Levee of the American River at Cal Expo Sacramento, California	M. Shriro et al. (2014a)
Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 3—Crown Trench Seepage Test, Northern Levee of Twitchell Island in Rio Vista, California	M. Shriro et al. (2014b)
Influence of Tree Roots and Mammal Burrowing Activity on Levee Integrity: Volume 4—Field Evaluation of Burrowing Animal Impacts and Effectiveness of Remedial Measures	Cobos-Roa et al. (2014b)
Influence of Tree Roots and Mammal Burrowing Activity on Levee Integrity: Volume 5—Slope Stability, Modeling and Analysis	In preparation
Influence of Tree Roots and Mammal Burrowing Activity on Levee Integrity: Volume 6—Final Conclusions	In preparation
Three-Dimensional Imaging, Change Detection, and Stability Assessment during the Centerline Trench Levee Seepage Experiment Using Terrestrial Light Detection and Ranging Technology, Twitchell Island, California, 2012	In preparation
Tree Root Architecture—How and Where Do Tree Roots Grow On and In Levees?	In preparation
The Influence of Vegetation on Levee Past Performance—a Review of Historic Data Based on the Levee Evaluation Program Database	Punyamurthula and Musto (2014)

candidate (Zanetti 2010), and included extensive study of the architecture of large tree root systems mechanically uprooted from levees comprising coarse, gravelly soils. Additional studies included measuring rates of root decay and examining noninvasive techniques to map tree roots. All studies have been reported in a series of journal papers as well as Zanetti's dissertation and several conference proceedings.

Austria

A long-term series of prototype-scale experiments has been conducted by Lammeranner and others at the Institute of Soil Bioengineering and Landscape Construction, University of Natural Resources and Life Sciences, Vienna, Austria. They have constructed a test levee with a rectangular alignment, forming an enclosed basin that may be filled with water to simulate flood loading. A variety of vegetation treatments (i.e., brush mattresses, dormant willow cuttings, grass and herbs) have been applied to segments of the test levee, and effects on seepage, soil properties, and development of above- and belowground components of the plants have been monitored. This work is unique in that it considers levees designed to include specific vegetative components rather than levees supporting natural, volunteer vegetation. Most of this work has been reported at international conferences.

1.7 Scope of this Document

This report is intended to produce a synthesis of findings of the CLVRP, ERDC research on levee vegetation, and relevant work performed in Europe and elsewhere that were available before early 2014. It is important to note that the scientific literature on many of the topics and specific projects treated in this report is continually expanding, and thus, coverage of recently emerging results may be uneven. Besides reporting research findings in summary form, a key objective is to identify points of consensus that have emerged, data gaps that exist, and issues that remain controversial or unresolved.

Available information for this synthesis was organized into the topics indicated by chapter titles for reporting purposes:

1. Root Architecture
2. Noninvasive Detection of Roots
3. Root Strength
4. Root Decay
5. Water Erosion
6. Treefall
7. Burrowing Animals
8. Seepage and Piping
9. Slope Stability
10. Risk Analysis
11. Flood Fighting
12. Inspection
13. Levee Design

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2 Woody Plant Root Architecture on and around Levees

Abstract
An assessment of the effects of trees on earthen flood control levees requires information about the size and spatial distribution of their roots. This information is very difficult to obtain, and it usually requires some type of excavation to expose part or all of root systems. State-of-the-art technology includes excavation of roots using compressed air and imaging of the exposed roots using ground-based Terrestrial Light Detection and Ranging scans. This chapter presents the findings of five studies involving excavation of pits or trenches to reveal portions of tree root structures on levees and two studies involving exhumation of entire root systems of selected levee trees. A third exhumation study revealed the entire root structure of a tree not growing on a levee. The studies indicate that root numbers and biomass decline exponentially with depth and with distance from the tree. Most roots are confined to the top 1 meter (m) of soil and are within the dripline of the tree, but exceptional tree roots occur at greater depths and distances, particularly from cottonwoods (*Populus* spp.). Trees growing on levee slopes differ from those on hillslopes in that root numbers, extent, and biomass tend to be higher toward the bottom of levee slopes. Tree species and environment are key influences on root architecture for a given tree.

2.1 Relevance to Levee Performance

Subterranean parts of woody plants are of great concern when risks from trees growing on and near levees are assessed. Living and dead roots have been hypothesized to create preferential flow pathways that induce seepage through or under embankments that triggers piping erosion and may ultimately lead to catastrophic failure. Conversely, if roots cross potential failure planes, they can reinforce soils and reduce the risk of slope instability such as sliding or slumping.

Analysis of potential root-induced seepage (e.g., Corcoran et al. 2011) and root reinforcement of slopes (e.g., Danjon et al. 2008) both require information on the size and spatial distribution of roots (referred to here as “root architecture”) in levee embankments. Furthermore, the risk of levee damage caused by treefall when trees are overturned by the forces of wind and water is directly related to root architecture, as the size of the root ball is partially governed by root depth and distribution.

Regulations regarding the dimensions of vegetation-free zones and variances from these regulations all rely on assumptions regarding tree root architecture. Science regarding root architecture for a wide range of plant species and ecoregions is expanding rapidly, but much fewer data have been published specific to woody species on flood-control levees. The

discussion below briefly describes destructive[3] field methods for studying root architecture and summarizes the results of studies of tree root architecture on levees. Noninvasive root detection technology is reviewed in Chapter 3, "Noninvasive Detection of Tree Roots within and adjacent to Levees."

2.2 Destructive Field Methods

The spatial distribution of roots, their dimensions, and their biomass may be studied at the scale of individual roots, individual trees, or stands of trees. Environmental variables (e.g., soil texture, soil moisture, season, slope, wind loading) and internal variables (e.g., tree size, age, and species) exert varying levels of influence on root architecture based on the spatial scale in question. Root architecture may be studied using nondestructive (noninvasive) techniques or various forms of excavation (Danjon and Reubens 2008). A range of noninvasive techniques have been tested or evaluated for root detection in levees; additional information is found in Chapter 3, "Noninvasive Detection of Tree Roots within and adjacent to Levees."

2.2.1 Trenches and Pits

Several workers have described root systems based on destructive sampling around trees on levees. Shields and Gray (1992) presented the results of profile wall excavations conducted on sandy Sacramento River levees on the right descending bank of the Sacramento River just upstream from Sacramento in 1986. Vertical walls were created by excavating 1.2-m-deep trenches, and the cross sections of roots 1–30 mm in diameter that were exposed in the walls were manually mapped using colored markers on clear overlays secured to the vertical trench wall (Figures 2-1a and 2-1b). The locations and diameters of the roots were then digitized from the clear materials in the office. Trenches were located in stands of herbaceous vegetation, along the driplines of four species of trees, and through the middle of a clump of elderberry bushes.

Similarly, Chambers et al. (2008) conducted trench excavations in clay and silt soils to expose the roots of nine species of trees growing adjacent to and on levees in New Orleans, Louisiana, in 2007. Trenches were located between selected trees and the crests of levees or floodwalls, were a maximum of 3 ft deep and 10 ft long, and ran parallel to levee or floodwall centerlines (Figure 2-2). Profile wall mapping procedures were employed to map roots greater than 0.5 in in diameter for 79 trees ranging in diameter from 13 to 65 in and in height from 28 to 110 ft. Harder et al. (2010, 2011) and Harder (2012b) manually excavated trenches in Sacramento River levees to examine interactions between tree roots and slurry cutoff walls (Table 2-1).

Corcoran et al. (2011) reported the results of excavation of selected quadrats adjacent to trees on levees at five sites in four locales (Sacramento, California; Burlington, Washington; Albuquerque, New Mexico; and Vicksburg, Mississippi). The quadrats each measured 1 square meter (m^2) and were excavated using hand tools or compressed air guns. The purpose of the excavations was to furnish validation data for noninvasive root mapping studies. At each site, four quadrats were

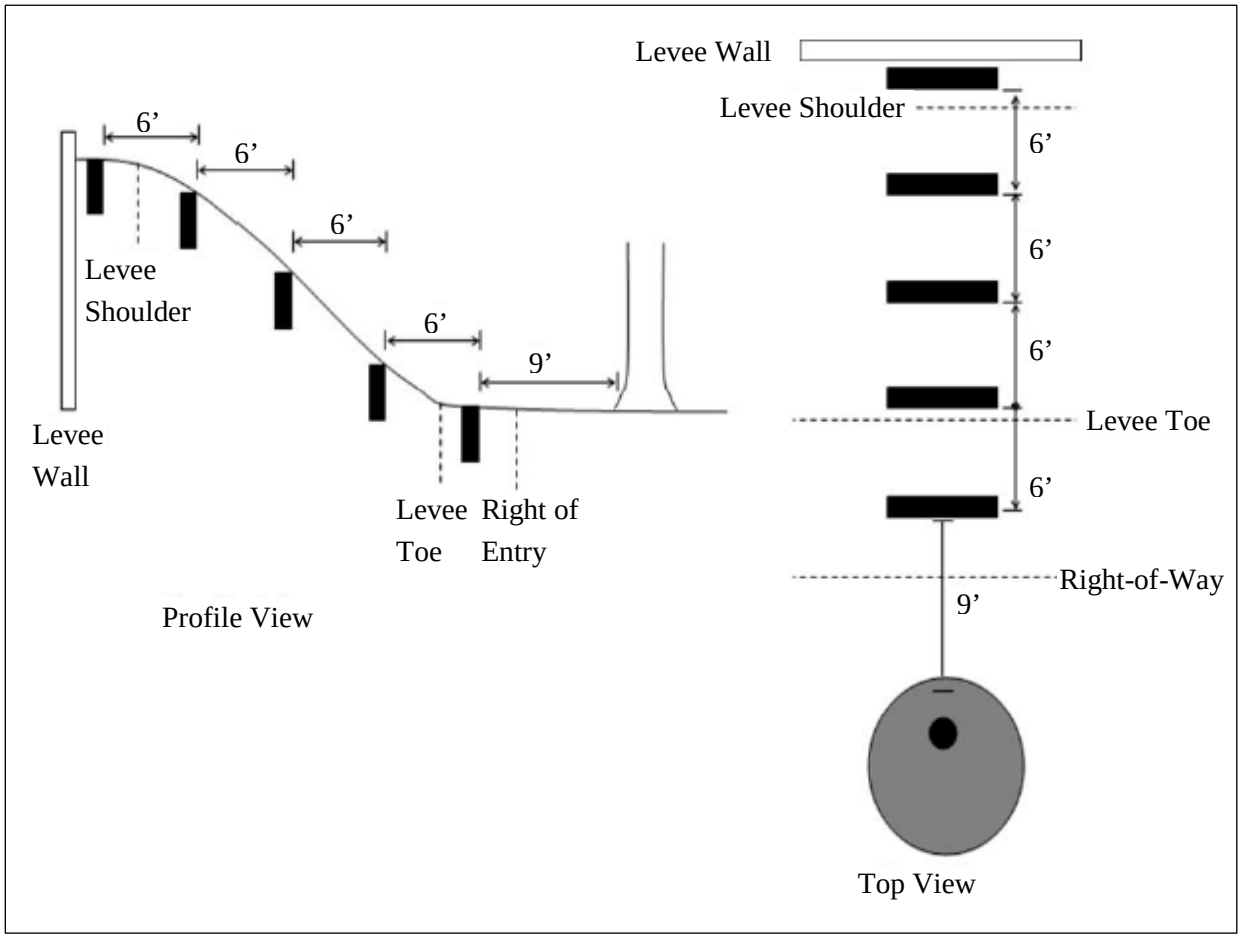
[3] Excavation that kills or damages the subject roots or tree.

Source: Gray et al. 1991

Figure 2-1a. Profile Wall Excavation of Sandy Levee to Examine Root Architecture

Source: Gray et al. 1991

Figure 2-1b. Grid Used to Facilitate Mapping Roots on Clear Acetate



Black boxes represent an idealized trench placement. The first root profile trench cut for each tree (grey circle) generally was placed at least 9 ft from the base of a tree in the direction of the levee wall and parallel to it. Successive root profile trenches were spaced approximately 6 ft closer to the levee crown than each preceding trench. Successive trenches were excavated until there were no roots greater than 0.5 in in diameter or environmental conditions did not permit additional trenches.

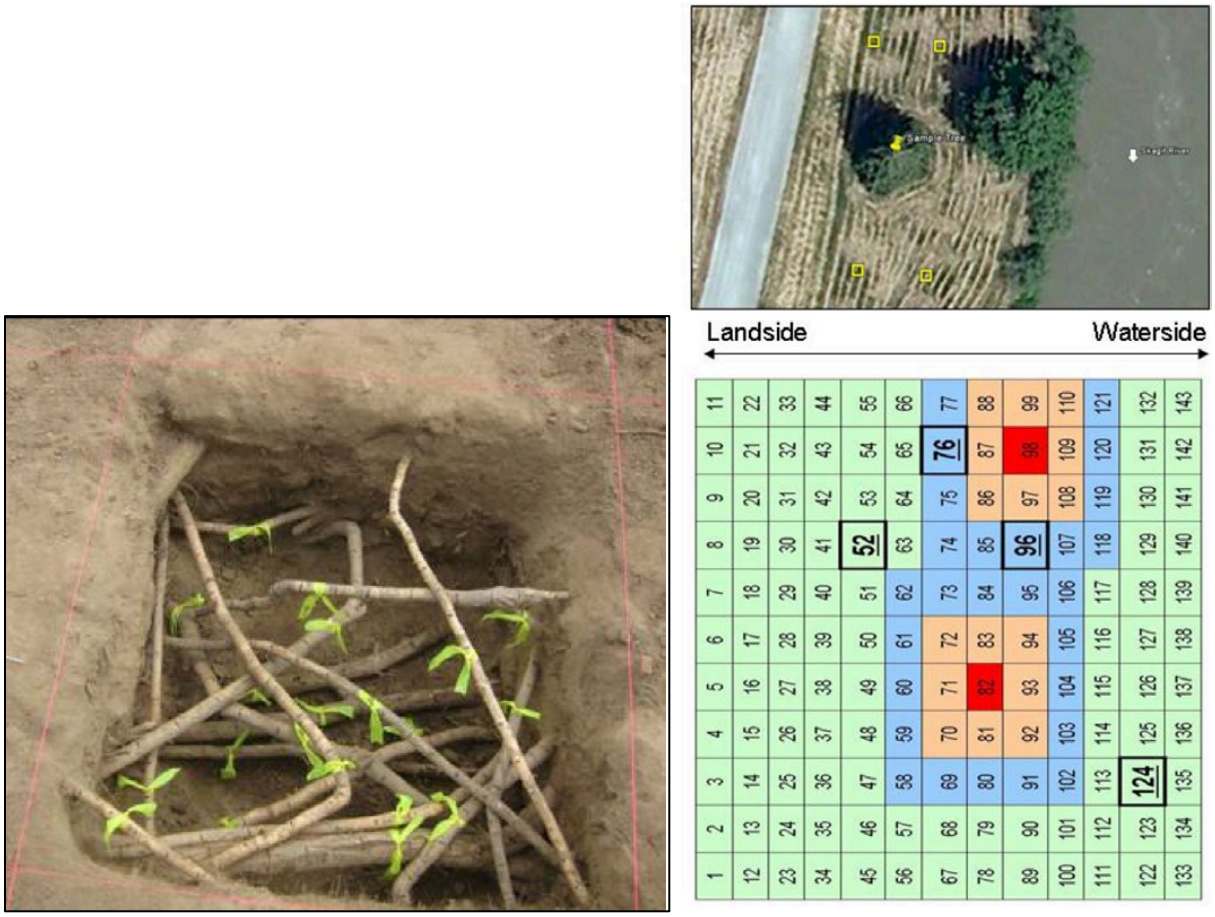
Figure 2-2. Schematic Showing Location for Root Wall Profile Trenches Used by Chambers et al. (2008)

Table 2-1. Manual Excavation of Trenches in Sacramento Levees to Examine Interactions between Tree Roots and Slurry Cutoff Walls

Site F, east levee of the Sacramento River in the Pocket Area of Sacramento (N38.497081°, W121.557441°)	Black walnut tree growing 4 ft landward of levee crest and 35 ft from levee centerline and soil-cement-bentonite slurry cutoff wall in a widened levee section.	
Site B, near Levee Mile 5.6 (N38.4889°, W121.5513°)	Two valley oak trees growing on the landside slope of the levee approximately 4 ft below the levee crown.	
Site G near Levee Mile 4.8 (N38.4995°, W121.5579°)	Two valley oak trees situated approximately 8 ft waterward of the waterside levee toe. Large cottonwoods were growing on the riverbank about 50 to 100 ft away from the levee centerline and soil-cement-bentonite wall.	

Source: Site B and G photos from Harder 2012b

selected from a sampling grid using a stratified random sampling protocol. The sampling grids were oriented parallel to the levee alignment and extended to the canopy line with the sample tree approximately in the center. Two quadrats were selected from the portion of the grid near the tree (inner domain) and two were selected from the portion away from the tree (outer domain), as shown in Figure 2-3. Excavations proceeded in 20-centimeter (cm) lifts to ultimate depths of 60–100 cm (Figure 2-3). Small roots were clipped or collected by sieving soil samples and weighed in the laboratory while the locations and sizes of larger roots were recorded using digitizers. The volume and mass of very small, micro-scale roots were estimated based on the total organic content of soil samples.



The grid shows a typical fully excavated 1-m^2 grid cell showing the large roots depicted in the photo. Grid cells with bold borders were randomly selected for excavation; tree locations shown in red.

Figure 2-3. Stratified Random Pit Excavations Used for Root Studies by Corcoran et al. (2011). The pit shown in the photo on the left corresponds to cell number 82 in the grid shown on the right.

2.2.2 Complete Exhumation

In contrast to studies that have sought to characterize root architecture based on the exposure of roots by rectangular trenches or pits, other investigators have attempted to exhume all (or nearly

all) of the root structure of individual trees to study their architecture (Danjon and Reubens 2008). Exhumation has been performed using manual tools or compressed air ("air knife"), or by pulling with mechanical equipment. For example, Zanetti (2010; also see Zanetti et al. 2008, 2009a, and 2011a) describes exhumation of 186 tree root balls representing nine common species at 10 sites in southeastern France using a track hoe (Figure 2-4). Both flood-control levees and permanently loaded embankments (dams and canal levees) were included in the study, and four of the six sites for which soil gradations were provided had fill with significant (up to 84%) gravel (greater than 5 mm). Roots were exposed by shallow excavation of the surface and then uprooted by pulling with the track hoe using chain slings. Large broken roots were marked and accounted for in the subsequent manual measurement of root morphology, which was conducted for 99 of the extracted root systems. In addition to manual measurements, about 26 stumps were scanned using Terrestrial Light Detection and Ranging (T-LiDAR) to obtain digital, 3D representations.

Source: Zanetti 2010

Figure 2-4. Mechanical Excavation of Tree from Levee and Manual Measurement of Root Morphology

Chung and Berry (2012) and Chung (2013) exposed entire root structures of selected trees growing on or adjacent to Sacramento River and San Joaquin River levees by blowing soil away from the roots with compressed air (pneumatic excavation or air knife) (Figures 2-5a and 2-5b). Loosened soils were sometimes removed using a vacuum system. Aboveground portions of trees were cut about 1.4 m above the ground before root exposure, and exposed roots were sometimes stabilized using metal fence posts.

Root systems of valley oaks and cottonwoods growing on lower waterside levee slopes or at the waterside toe were exposed and studied. The cottonwoods studied by Chung and Berry (2012) tended to be younger and smaller than those that were associated with roots examined by Harder as described above. However, the wide-ranging roots reported by Harder at Site G were mapped by Chung and Berry (2012) and their team.

Figure 2-5a. Pneumatic Excavation of Valley Oak Roots with Air Knife, Site G, Sacramento

Figure 2-5b. Valley Oak after Partial Exposure of Roots Using Air Knife, Site G, Sacramento

Before and after root exposure, 3D images of the ground surface and the above- and belowground portions of the tree were obtained in situ by scanning with ground-based T-LiDAR from multiple locations around the tree. Corcoran et al. (2011) report the use of pneumatic excavation and Light Detection and Ranging (LiDAR) scanning to expose and map the root structure of a single tree not growing on a levee. Cobos-Roa et al. (2012c) excavated trenches on a levee slope near a dead stump, a living tree, and herbaceous vegetation and used ground-based T-LiDAR scans to characterize soil stratigraphy, animal burrows, and root architecture. Trench wall mapping was enhanced by using reflective targets and metallic paint to highlight roots, burrows, and stratigraphic contacts, and trench walls were removed in vertical "slices" marching up the levee to obtain a fully 3D map of subsurface features and stump architecture. Additional work at this site is described in Chapter 9, "Effects of Trees on Seepage and Piping in Levees."

Ground-based T-LiDAR scans of exposed (unearthed) root structures produce millions of x, y, z points that represent root surfaces. These may be displayed graphically for simple visualization, but abstraction of these huge datasets to yield quantitative information requires sophisticated data reduction and analysis techniques (Zanetti 2010, Chung et al. 2013, Chung 2013). Using special hardware and software, LiDAR datasets may be used to generate numerical and graphical representations of root distributions in planar (Chung et al. 2013) or annular (Chung 2013) sections. These data subsets may be used to compute spatial biomass distributions for single roots or whole tree root systems. Additional analysis is facilitated by mathematically representing roots as vectors that capture root branching patterns, growth angles, and lengths (Chung et al. 2013).

2.3 Findings of Invasive Field Investigations

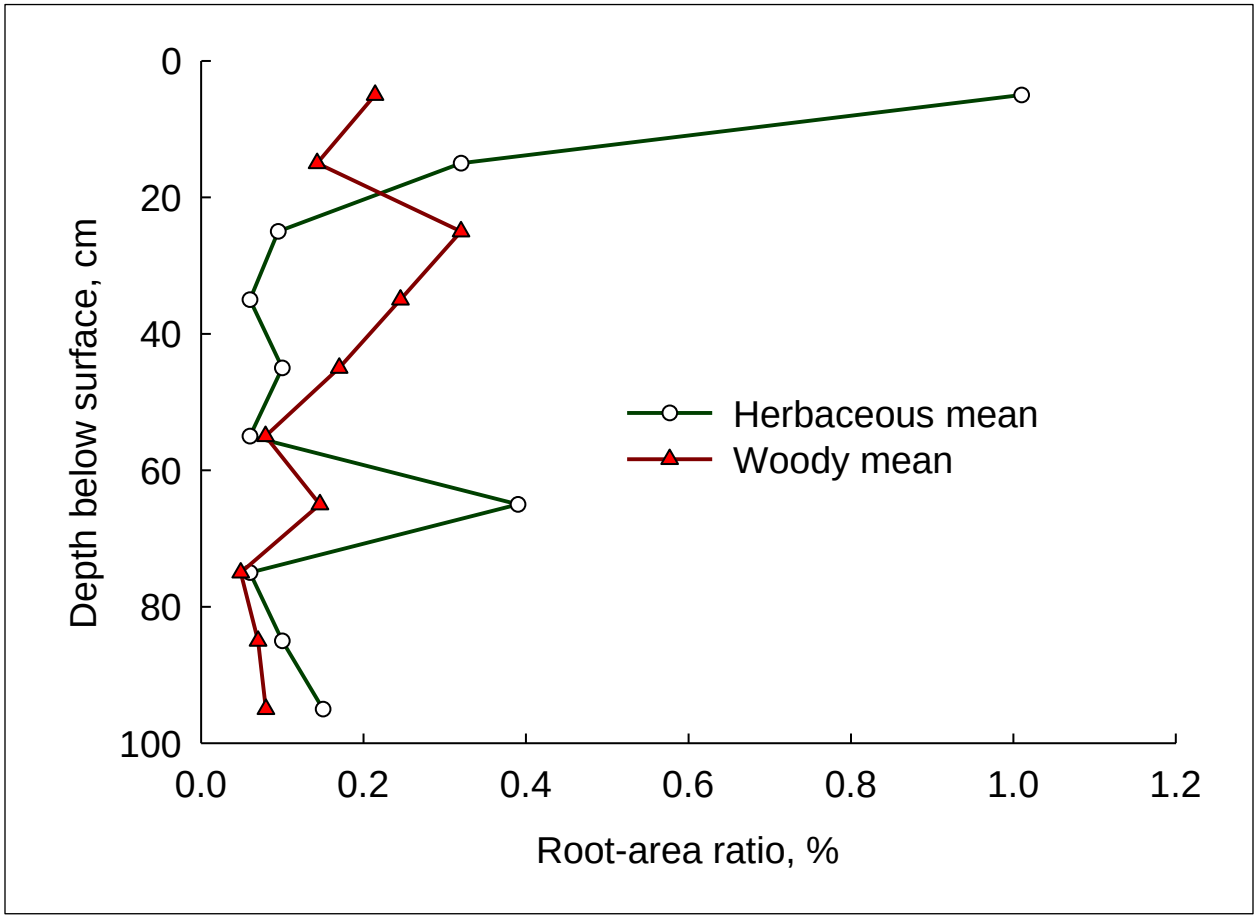
Shields and Gray (1992) reported the results of profile wall mapping of trenches around trees and herbaceous cover on Sacramento River levees. Root-area ratios (RARs)[4] varied from 0.001% to 2.02% (mean = 0.17%, standard deviation = 0.30%). Corcoran et al. (2011) reported root volume ratios ranging from 2.5% to 7.8%, considerably higher than the RARs reported by Shields and Gray (1992). However, the stratified random sampling protocol used by Corcoran et al. (2011) positioned several units (pits each measuring 1 m^2) very close to trees (Figure 2-3) while Shields and Gray (1992) trenched at tree driplines, except for one trench that passed through the center of a clump of elderberry bushes and generated the highest RAR. Furthermore, data reported by Corcoran et al. (2011) showed that when volumes of "micro-roots" inferred from soil total organic content were excluded, the root volume ratios ranged from 0.06% to 4.35%. About 76%

[4] Root-area ratio is a dimensionless measure of the density of roots in a given mass of soil. It is found by dividing the sum of the cross-sectional areas of all roots in a given vertical plane by the area of the plane. The RAR lends itself to use with datasets derived from sites where roots have been mapped in the vertical walls of excavated trenches.

of root volume comprised roots greater than 2 cm in diameter when the "micro-roots" were excluded.

2.3.1 Vertical Distributions

Root numbers decline exponentially with increasing root diameter (i.e., large roots are far less frequent than small roots). Root frequency and RAR decline exponentially with depth (Figure 2-6) (Shields and Gray 1992, Chambers et al. 2008, Gianetta et al. 2013), and rates of decline vary by species (Chambers et al. 2008, Table 2-2). Profile wall mapping does not account for roots deeper than the trench depth or vertically oriented roots. Shields and Gray (1992) noted that roots remaining around a dead oak stump angled sharply downward, creating a conical form



Source: Shields and Gray 1992. Data are mean values from profile-wall excavations in Sacramento River levees. Woody vegetation values were computed using data from trenches excavated underneath the driplines of selected trees growing on waterside levee slopes.

Figure 2-6. Variation of Root-Area Ratio with Depth below Levee Surface

similar to those exposed by Chung and Berry (2012). Chung (2013) reported that excavated trees growing on levee slopes had a strong vertical taproot, whereas floodplain trees did not. Zanetti et al. (2011a) reported long taproots for cottonwoods (*Populus* spp.).

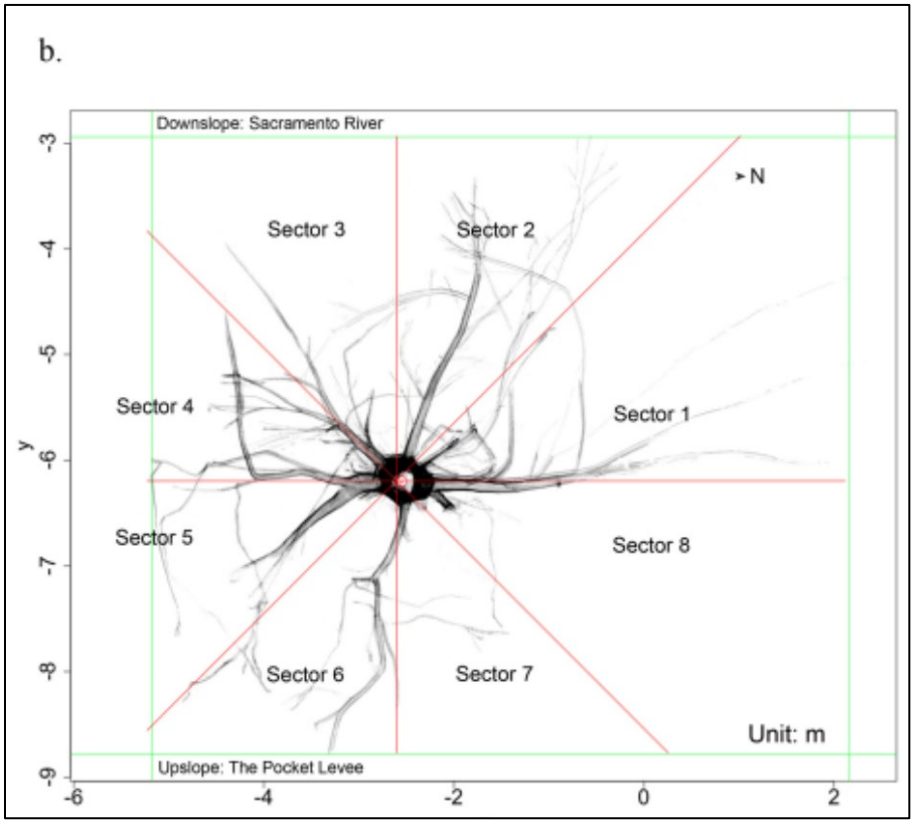
Chung (2013) reported that root biomass was located primarily in the upper 1 m of soil, and at a consistent depth regardless of direction from the tree (upslope, downslope, or parallel to the levee line). Approximately 90% of total biomass measured was in the top 1 m of soil. However, a few large roots have been found at greater depths on and adjacent to levees. For example, Chambers et al. (2008) conducted a study (subordinate to their larger-scale effort described above) along abandoned Mississippi River levees to examine the occurrence of large-diameter roots at depths greater than 3 ft. Ten trees representing five species were studied, and at least 20 roots were encountered at depths greater than 4 ft and less than 8 ft (the bottom of the excavations). This represented a small fraction of the total number of roots.

2.3.2 Horizontal Distributions

Chung (2013) found that root biomass was distributed roughly parallel to the slope surface and declined exponentially with radial distance from the tree, with the rate of decline much greater for valley oaks than for cottonwoods. For both species, the rate of decline was much greater in the upslope direction than in the downslope direction (Figure 2-7a), most likely because of biomechanical interactions between the trees on levee slopes and the levee structure. The major woody laterals extending parallel to the levee line in either direction had greater total biomass and root number than comparable roots in either the upslope or downslope direction.

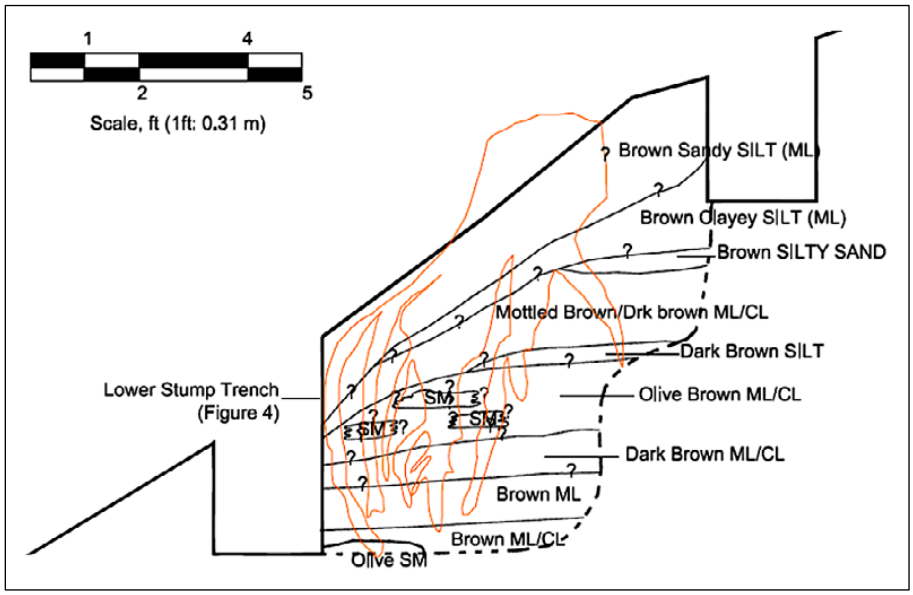
These patterns occurred regardless of the orientation of the levee with respect to cardinal (compass) directions.

Chambers et al. (2008) noted an exponential decline in root numbers and biomass with distance from the trunk. Trees growing on levee slopes differ from those on hillslopes in that root numbers, extent, and biomass tend to be higher toward the bottom of levee slopes (Chung et al. 2013, Berry and Chung 2012, Cobos-Roa et al. 2012c, Zanetti 2010) (Figure 2-7 and Figure 2-8), while opposite patterns appear on hillslopes, perhaps to secure anchorage (Danjon et al. 2008). Chambers et al. (2008) found that the maximum lateral extent of roots varied widely from tree to tree, with most roots confined to zones much smaller than the canopy dripline. However, exceptional cases produced a few roots at large distances from the tree stems. Weibull probability density functions were fit to the data to predict the distance from the tree in the direction of a levee or floodwall that would contain 95% or more of the roots of a given size. An excerpt of the resulting values is provided in Table 2-2.



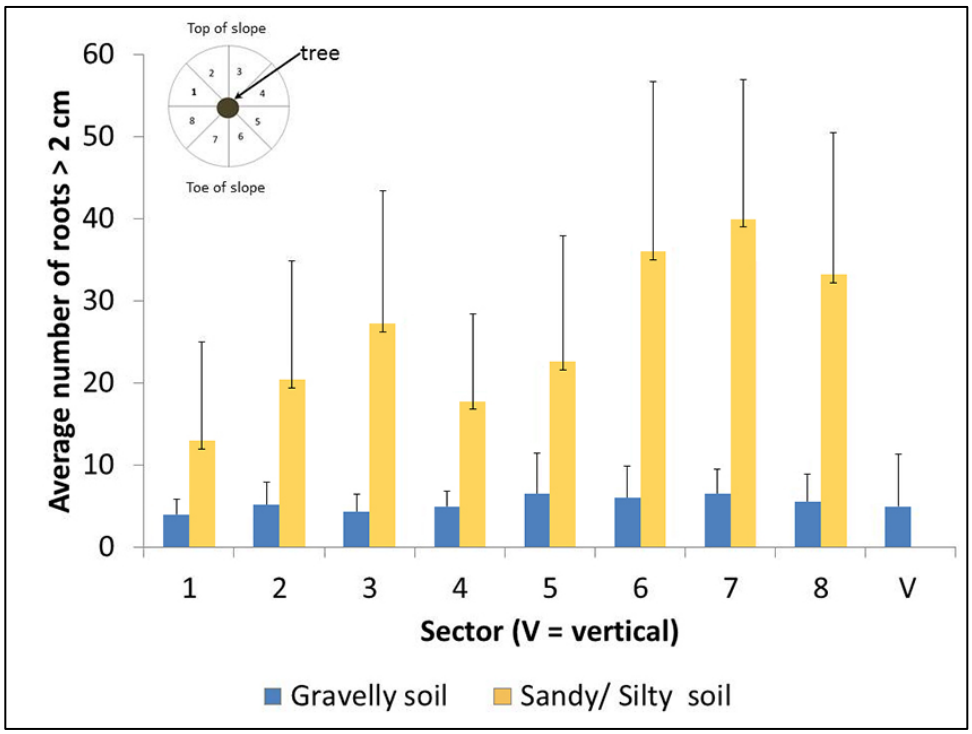
Source: Chung 2013

Figure 2-7a. Root System for Valley Oak at Site G, Sacramento



Source: Cobos-Roa et al. 2012c

Figure 2-7b. Root Systems for Dead Eucalyptus Stump Showing Asymmetry with Roots Concentrated Downslope



Source: Zanetti 2010

Bars indicate the means for seven trees growing in gravelly soils and five trees growing in sandy/silty soils. The inset sketch is a plan view of a tree on a levee slope showing the orientation of circular sectors that are used as x-axis labels.

Figure 2-8. In Gravelly Soils, Root Numbers Greater in Downslope Direction for Trees Growing on Levee Slope

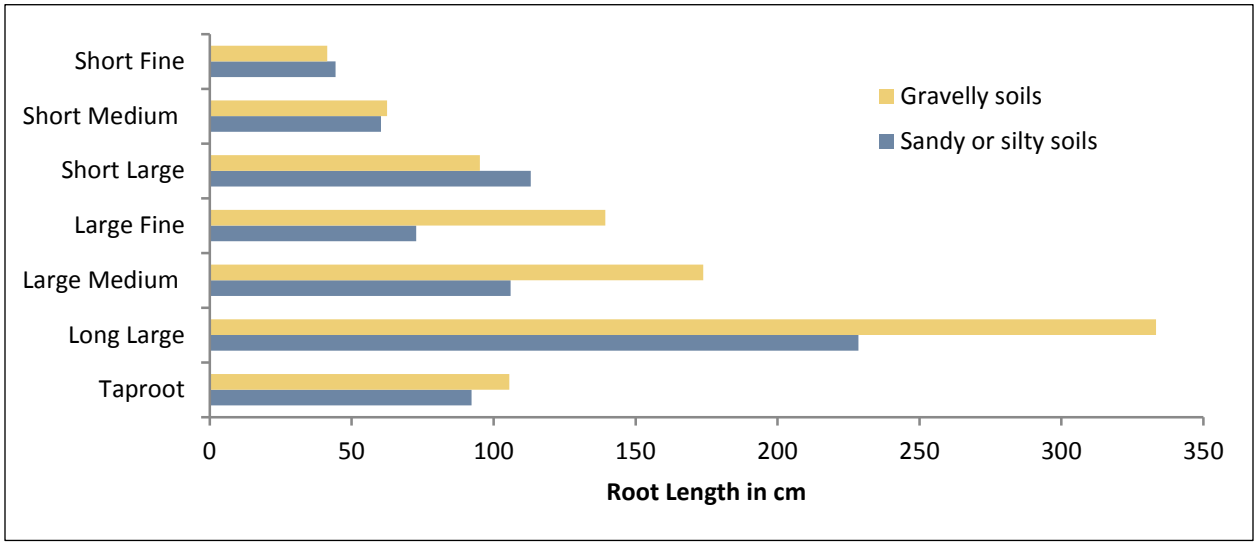
Table 2-2. Distances from Tree Trunks (in feet) that Contain the Specified Percentage of Roots Larger than 0.5 Inch Diameter by Species

Species	50%	90%	95%
Bald cypress	10.7	15.8	18.0
Drake elm	10.5	12.7	13.6
Live oak	12.0	21.5	25.6
Pecan	15.0	30.9	37.8
Slash pine	10.6	16.4	18.9
Sugarberry	10.4	16.3	18.9
Sycamore	13.8	27.1	32.7
Tallow	11.4	22.3	27.1
Water oak	10.9	17.9	21.0

Source: Chambers et al. 2008

Note: Weibull probability density functions were fit to data from 79 profile-wall trench excavations in 2007 in the New Orleans metropolitan area.

A key objective of the New Orleans study by Chambers et al. (2008) was to define the maximum extent of root growth. High variation from tree to tree was observed, and Table 2-2 indicates that roots from certain species were found 20–40 ft from the parent tree. Zanetti et al. (2011a, 2015) reported root length on the order of 3 m for cottonwood (*Populus* spp.) and black locust (*Robinia pseudoacacia*) on French levees. Root lengths were greater in coarse (gravelly) materials (Figure 2-9).



Source: Zanetti 2010

Bars show the means for a given category; total number of roots in all categories = 282. Roots tend to be larger and longer in gravelly soils.

Figure 2-9. Effect of Root Type and Soil on Root Length for Trees Growing on French Levees

Some workers have attempted to generate empirical relations between root system dimensions and aboveground tree dimensions (Chung 2013). Berry and Chung (2012) reported that the levee trees they studied had a maximum upslope root extent of only 1.25 times the crown radius (for root diameters greater than or equal to 1 in). Further, they noted that the trunk diameter or diameter at breast height (dbh) was a better predictor of root extent. The literature indicates a lack of useful correlation between crown radius and root extent, although such a relation is often assumed (Schwarz et al. 2010). Zanetti (2010) found a strong correlation ($r^2 = 0.96$) between the age/diameter ratio of the largest roots and the age/diameter ratio of tree trunks for six tree species growing on French levees.

In contrast to the findings reported by Berry and Chung (2012), Harder (2012b) reported cottonwood roots of significant size (diameter greater than 1 in) that occurred more than 100 ft from the tree trunk. French work involving excavation of large numbers of trees on levees has shown that local soil and moisture govern rooting patterns and that extension of sizable roots beyond 1.75 times the tree crown radius is common, with large individuals of several species (*Salix*, *Populus*, *Robinia*, and *Platanus*) often extending large roots more than 10–12 m from the trunk (Zanetti et al. 2015). Moreno et al. (2005 in Zanetti et al. 2015) reports that *Quercus ilex L.*

develops roots up to 33 m long, spanning up to seven times the surface of its canopy in Mediterranean forests (arid climates and sandy soils, but not on levees).

2.3.3 Species versus Environment as Controls on Whole-Tree Root Architecture

Zanetti (2010) examined root architecture for trees growing on French levees and proposed four architectural categories:

(1) Surface root systems, composed of roots parallel to the soil surface, spreading between 0 and 70 cm deep;

(2) Mixed systems composed of a well-developed surface type and one or two small adventitious[5] types, rarely more than 1.5 m deep;

(3) "Fasciculate" (bundled) root systems consisting of a large number of roots often growing at an oblique angle, usually distributed between 0 and 1.5 m deep; and

(4) Adventitious systems, with a large adventitious taproot relative to the size of the stump that can be anchored at more than 2 m deep.

Standard work in tree root system architecture (e.g., Stokes and Mattheck 1996) has identified three basic morphologies: plate (#1 above), heart (#2 above, perhaps), and tap root (#4 above). In studies on French levees, species accounted for very little of the variation in root architecture among the four categories above, while environmental conditions such as soil type, access to water, and local constraints were much more influential (Zanetti 2010, Vennetier et al. 2014). In fact, in homogenous soils, different species had the same root architecture: black locusts, poplars, and oaks had same root system architecture in the sandy soils of Loire levees (C. Zanetti, personal communication 2013). Considering all sites, most species exhibited at least two of the four types of root architecture. Roots grew in ways to efficiently access water and nutrients. In fine materials (sandy or silty soils), the density of roots per stem was high and fasciculate architecture was common. In gravelly soils, root density was lower, with fewer but larger diameter roots. In porous materials, roots concentrated near the surface where the primary source of water was rainfall, but exhibited mixed or adventitious architecture when they had access to groundwater. Large taproots (about 3 m long) were observed for poplars growing in coarse materials over a water table. Zanetti (2010) did find that root growth rates were strongly related to tree species.

In contrast to reports by Zanetti (2010), studies of roots of levee trees in New Orleans showed strong variation by species (Table 2-2), but homogenization of levee soils did not allow a comparison of the effect of soil texture on root extent (Chambers et al. 2008). Chung (2013) and Harder et al. (2011) noted vastly different rooting patterns for valley oaks and cottonwoods

[5] Zanetti used the term "adventitious" to refer to vertical taproots. In most technical literature this term describes roots that grow from parts of the plant where they do not normally originate, for example from the trunk of a tree above the root crown.

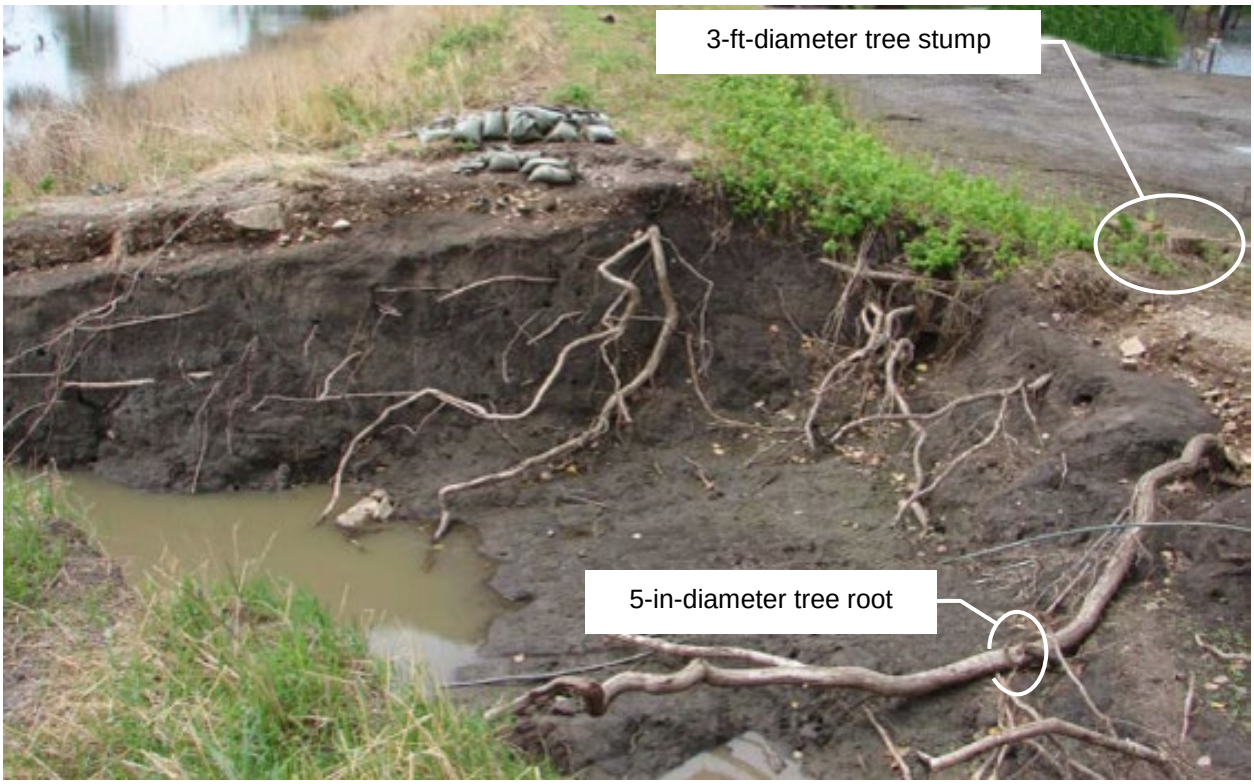
(Figure 2-10), although Chung noted similar upslope/downslope asymmetry in biomass distribution for these two species. Large cottonwood roots that fully penetrated an earthen levee in the Midwest (Figure 2-11) were exposed when the levee was overtopped during the 2008 flood (Harder et al. 2009). The impacts of these roots on levee performance are discussed in Section 6.4.

Gold arrows indicate large cottonwood roots traversing the site.

Figure 2-10. Root Systems of Two Valley Oaks Exposed by Pneumatic Excavation, Site G, Sacramento

Roots often avoid extremely dense or compacted soils (Chung and Berry 2012, Gianetta et al. 2013), but Lammeranner (2012) reported successful cultivation of shrubby willows in a compacted levee embankment. Willows were carefully planted in four standard bioengineering configurations (dormant cuttings, living brush mattresses [longitudinal], living brush mattresses [transversal], and jute netting mulch seeding) and irrigated to aid establishment. They developed shallow but dense growths of fine roots despite soil dry densities between 1.886 and 2.028 grams per cubic centimeter (g/cm^3) (Lammeranner et al. 2008).

Photograph of Cap au Gris Site 1 levee breach Looking toward the Mississippi River (July 22, 2008).



Photograph of Cap au Gris Site 1 levee breach showing numerous exposed tree roots (July 22, 2008).

Source: Harder et al. 2009

Figure 2-11. Cottonwood Roots Penetrating Failed Levee Embankment along Mississippi River, Cap au Gris, Missouri

2.4 Data Gaps

Reliable techniques for predicting the spatial extent of roots from rapidly and easily acquired data from aboveground observations are lacking (see Chapter 3, "Noninvasive Detection of Tree Roots within and adjacent to Levees"). Data on root architecture are limited to only a few tree species, with little replication by tree size, tree condition, or site conditions. Furthermore, available data indicate that root architecture on levees may differ from that found on hillslopes or flat surfaces, but this finding is not conclusive.

2.5 Points of Scientific Debate

Existing data clearly show that most tree roots are concentrated in the top 1 m of soil and within a zone surrounding the trunk that is smaller in horizontal extent than the canopy. However, there appears to be great variation from site to site based on soil conditions, other habitat factors, and tree species. The plots of data presented by Corcoran et al. (2011) described above reveal no systematic spatial trends. Data tables presented in Corcoran et al. (2011) show vertical distribution for small roots (those measuring less than 2 cm), and total volumes for roots greater than 2 cm for the entire 1-m^2- by 1-m-deep quadrat. These roots greater than 2 cm comprised an average of 76% of the root volume reported by Corcoran et al. (2011). Vertical trends in root numbers, volume, and biomass may have been obscured by the way the data were presented.

Furthermore, a few large roots extend farther than the norm both vertically and horizontally. Roots fully penetrating earthen levees have been exposed in failed levee sections. There is no recognized consensus on how to allow for the effects of such roots on seepage or windthrow potential in levee design or risk analysis. Root architecture studies are labor intensive; techniques and technology for more complete and efficient mapping are emerging, but there is no standardization of techniques.

Exposure of roots in failed levee embankments has been variously interpreted: roots either mitigated, triggered, or played no role in failure.

2.6 Potential Implications for Levee Vegetation Management

Most tree roots are confined to definite zones in the vicinity of the tree of origin and within 1 to 1.2 m of the soil surface, but infrequent exceptions occur wherein roots greater than 2 cm appear at depths greater than 1 m and at significant distances from the tree. Large cottonwood (*Populus* spp.) roots have been observed growing from 3 m to more than 30 m from the parent tree. German workers have reported that poplars produce wide-ranging roots. Completely excluding roots from the levee prism by excluding trees from the levee embankment and its environs is difficult if not impossible because of the wide-ranging growth of exceptional roots. When viewed at the scale of 3–30 m, root distributions are highly heterogeneous and 3D, but tend to occur in three or four general patterns that may be described as conical, disk-shaped, or

cylindrical. Tree species and environmental factors (e.g., soils, slope, hydrology) are highly influential determinants of root architecture.

Additional datasets based on careful trench excavation or complete root system exhumation might yield enough data to characterize the spatial distribution of roots by species and levee project, so that a probability density function could be used to assess the likelihood of roots extending beyond certain spatial limits, as was done by Chambers et al. (2008). If the presence of roots could be linked to the likelihood of certain failure modes, these functions might then be useful in levee failure risk assessments.

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3 Noninvasive Detection of Tree Roots within and adjacent to Levees

Abstract
A range of ingenious techniques has been developed for noninvasive (without excavation) detection of root architecture. This chapter summarizes three studies of root detection in levee embankments using noninvasive techniques. One study involved the experimental use of ground-penetrating radar, electrical resistivity, and electromagnetic induction at multiple levee sites. None of the methods tested were effective at all sites; roots or root zones were detected in fewer than one-third of the cases. Another study tested ground-penetrating radar and reported it unsuccessful, as it is suitable for certain soil textures only. One study examined the use of electrical resistivity to detect roots buried in containers of soil in the laboratory. Overall performance was poor, especially in finer textured (clay and silt) soils.

3.1 Relevance to Levee Performance

Subterranean parts of woody plants are of great concern when assessing the risks of trees growing on and near levees. As noted in Chapter 2, analyses of root-induced seepage, root reinforcement of slopes, and potential damage from tree windfall all require information on the size and spatial distribution of roots (referred to here as “root architecture”) in levee embankments. Further, the assessment of root contributions to slope stability also requires accurate root-architecture descriptions. Data on root architecture may be obtained through excavations, but these are labor intensive and destroy or severely damage the vegetation and the levee embankment. Noninvasive techniques potentially offer faster, cheaper ways to obtain root architecture data.

3.2 Available Technology

Root architecture may be studied using nondestructive (noninvasive) techniques or various forms of excavation. Noninvasive, remotely sensed techniques for mapping tree roots are of interest because root-excavation techniques tend to be labor intensive, usually involving rough work with mechanical equipment and more detailed excavation using hand tools. Excavation is practical for only a small subset of any given levee system, making accurate determination of root intrusion impossible for the entire system.

The science of noninvasive geophysical techniques for root study is advancing (Vanderborght et al. 2013, Guo et al. 2013a, Zhu et al. 2011 and 2013). A range of noninvasive techniques have been tested or evaluated for root detection in levees and found to perform poorly except when soil texture and moisture conditions are ideal (Chambers et al. 2008, Corcoran et al. 2011,

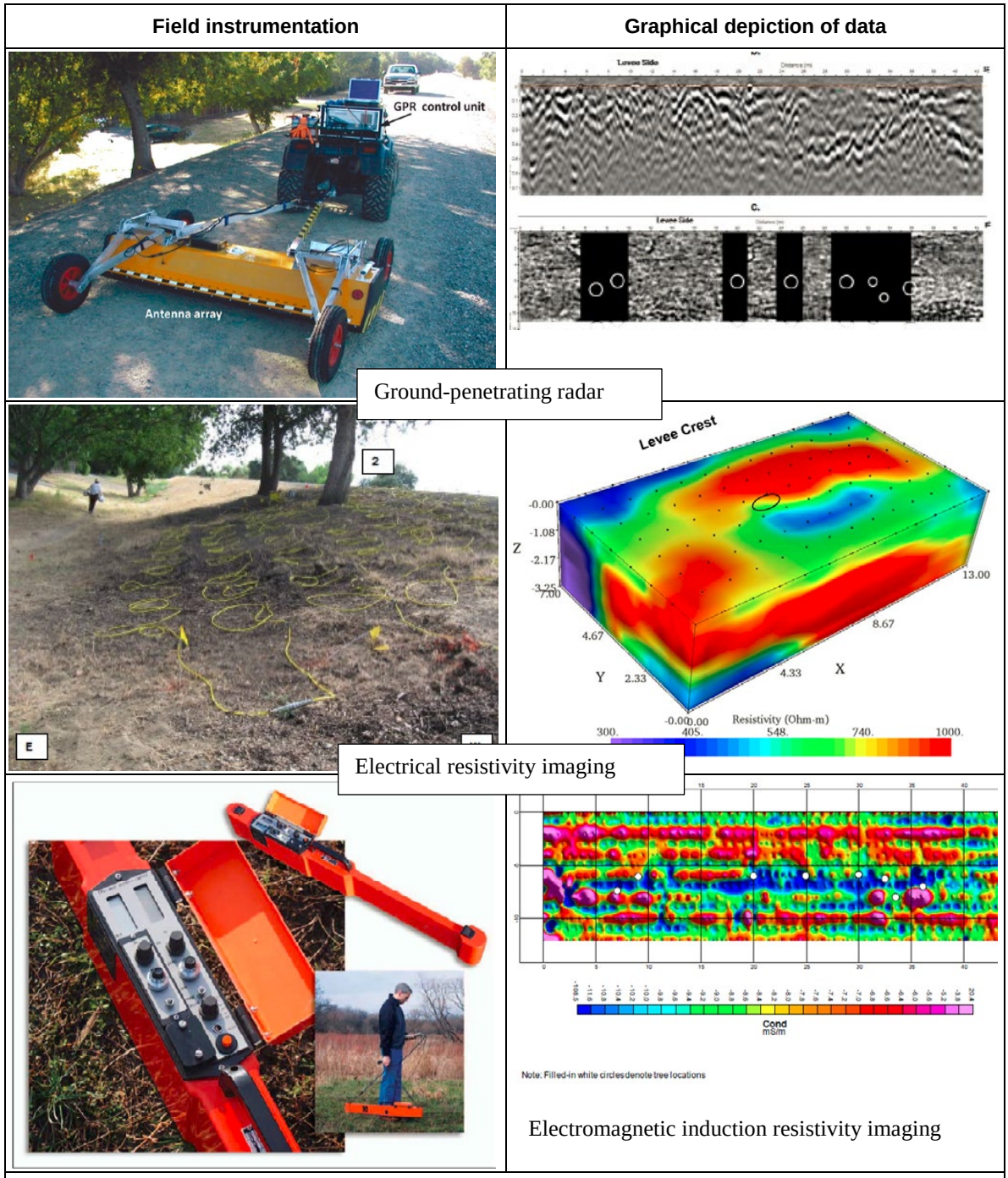
Zanetti et al. 2011b). Similar findings have been reported for more general applications of ground-penetrating radar (GPR) for tree root detection in sand (Hirano et al. 2009), for GPR detection of coarse roots (those greater than 2 mm) in a variety of settings, and for the electrical impedance method (Urban et al. 2011). Noninvasive techniques generate large quantities of data that must be analyzed using advanced techniques such as those developed for medical tomography (Danjon and Reubens 2008).

Corcoran et al. (2011) reported geophysical exploration of tree root architecture at nine sites (eight of which were levees) at seven locales with three noninvasive techniques: GPR, electrical resistivity imaging, and electromagnetic induction (Figure 3-1). All three methods were not employed at all sites:

- GPR was tested at five sites. The depth of the root zone was reported for three of the five sites.
- Electrical resistivity imaging was tested at seven sites. Useful root zone dimensions were reported for four of the seven sites.
- Electromagnetic induction was tested at six sites (five locales) and was reported to be effective at one of the six sites.

Corcoran et al. (2011) reported that the results of the various methods were often contradictory and inconsistent (Table 3-1). Excavation to reveal roots was performed around a single pine tree growing in moist sand at a nonlevee study site (Vicksburg, Mississippi). Similar calibration was not performed at the levee field sites. Root zones were sometimes detected, but individual root detection was reported for only one site (Portland, Oregon; GPR), as shown in Table 3-1. Some methods were confounded by buried stones or inclusions. Subsequent to the work described by Corcoran et al. (2011), USACE also applied geophysical techniques to root detection at a T-floodwall project in Missoula, Montana. Results were similar to those described above (M. Corcoran, personal communication 2013). Leslie and Heinse (2013) reported very limited success for application of electrical resistivity for locating pipes in forested soils, but metal pipes should be easier to detect than roots because metal is electrically more dissimilar to soil than roots are.

Zanetti et al. (2011b) reported that GPR was unsuccessful in detecting tree roots on levees. GPR performance was found to be strongly influenced by soil texture. Clay-silty soils strongly limit the electromagnetic signals, while gravelly materials generate many echoes, obscuring the useful data. Other workers report that GPR is strongly influenced by root biomass and water content (Guo et al. 2013b).



Note: From Corcoran et al. (2011).

Figure 3-1. Geophysical Instrumentation and Resulting Data for Noninvasive Root Characterization in Levees

Table 3-1. Summary of Noninvasive Root Detection Study Results

Locale	Soil	Tree(s)	Tree dimensions: dbh, dripline diameter, height (m)	Mapped lateral influence of tree root zone with respect to levee axis: parallel, perpendicular, depth (m)		
				ERI	GPR	EM
Sacramento, California	Silty sand	Valley oak	0.75, 16.8, 15	1.6, 1.5, 1.6	1.4, 1.7, 0.35	No correlation with root zone
Albuquerque, New Mexico	Poorly graded sand	Cottonwood	0.41, 10.7, 11	No correlation with root zone	Not tested	Not tested
	Well-graded sand	Two cottonwoods	0.58, 14, 12 and 0.27, 9.2, 9	No correlation with root zone	Not tested	Not tested
Burlington, Washington	Silty sand	Western red cedar	1.43, 12.2, 20	10, 10, 1.5 to 2	12, 12, 0.62	10, 10, –
Vicksburg, Mississippi	Lean clay	Southern red oak	0.29, 7.5, 7.5	3.6, 1.8, 1.0	4.5, 3.5, –	Not tested
New Orleans, Louisiana	Clay	Hackberry	0.64, not reported	Not tested	1, 1.8, –	No correlation with root zone
	Clay	Two oak stumps	1.1, not reported 0.90, not reported	Not tested	No results provided	No correlation with root zone
Portland, Oregon	Sand	Eight cottonwoods	Approx. 0.5 to 1.0, overlapping, approx. 10–15	No correlation with root zone	NA, 6.0, 0.5. Individual roots detected	No correlation with root zone
Lewisville, Texas	Fat clay	Post oak	1.1, 15, 10	3.5, 2.7, 1.5	Not tested	No correlation with root zone

Source: Corcoran et al. 2011. Excerpted from Vol II, Table 36.
Notes: approx. = approximately; dbh = diameter at breast height; EM = electromagnetic induction; ERI = electrical resistivity imaging; GPR = ground-penetrating radar; m = meters

Zanetti et al. (2009b, 2011b) also investigated the use of electrical resistivity to detect roots of six tree species under ideal laboratory conditions. Root samples from six different plant species (poplar, locust, oak, ash, maple, and willow) were used in tests as follows:

- For each species, three replicates of each of two diameter classes (3–4 cm and 6–7 cm) of roots of 35 cm length were tested for a total of 36 tested specimens.
- Root samples were buried 0.05 m deep in plastic containers filled with three types of soil (silt, sand, and gravel). Containers were kept inside a building to control temperature and moisture levels. Water content of the soils ranged from 5% (gravelly soils) to 6% (sandy soils) to 16% (silty soils).

- The differences in conductivity (inverse of the resistivity) of the soils with and without the presence of root samples were measured, and the distinctions between the types of materials, species, and position of the samples were analyzed. Instead of simple measurement of conductivity, complex conductivity spectra were observed to obtain spectral induced polarization.

Results were as follows:

- In most cases, the buried root samples increased the overall conductivity of the materials.
- Overall, performance was poor, especially in finer textured (clay and silt) soils. Sands and gravels provided the best conditions for detection of the roots, while root detection in clay or silt soils was found to be "probably impossible (or at least difficult) by conventional electrical conductivity measurements."
- Root orientation was important to detectability.
- Differences based on species were significant. For example, poplar roots gave the strongest signature, but ash roots were undetectable under the tested conditions.

The most recent publication derived from this work (Zanetti et al. 2011b) concluded that a field procedure, such as spectral induced polarization, that includes the measurement of the imaginary part of conductivity[6] would provide useful signals for the detection of extended root networks in levees. However, compared to a conventional geoelectrical survey, spectral induced polarization is a slow and expensive method. French research continues on the use of electrical resistivity for root detection with some modest (detection of greater than 5-cm-diameter roots that were less than 15 cm below the soil surface) but promising initial results (Renault n.d., Zanetti et al. 2013).

3.3 Data Gaps

Few field experiments using geophysical noninvasive approaches for root detection have been adequately validated using actual exposure of roots by excavation. The results of existing efforts to use noninvasive root detection system on levees are poor or inconsistent. The lack of field validation makes reported results of noninvasive detection of "root zones" of uncertain value.

[6] Ordinary conductivity is a measure of the response of a given material to a uniform flow of electric current. The response of a material to an alternating current requires the use of a property called admittivity (or admittance) rather than conductivity. It is measured using complex numbers, which are the sum of a real number and an "imaginary" number ($a + bi$), where $i = \sqrt{-1}$. Standard math texts contain explanations of complex and imaginary numbers.

3.4 Points of Scientific Debate

The poor record of noninvasive techniques to date calls to question whether they will ever be adequately developed to serve routinely for subterranean inspection of levee embankments and their environs.

3.5 Potential Implications for Levee Vegetation Management

The idea of noninvasive root detection is quite attractive as an efficient means of gathering crucial information for analyzing the effects of trees on levee stability and reliability, but no tested technology has been shown reliable for general or even limited application.

4 Root Strength

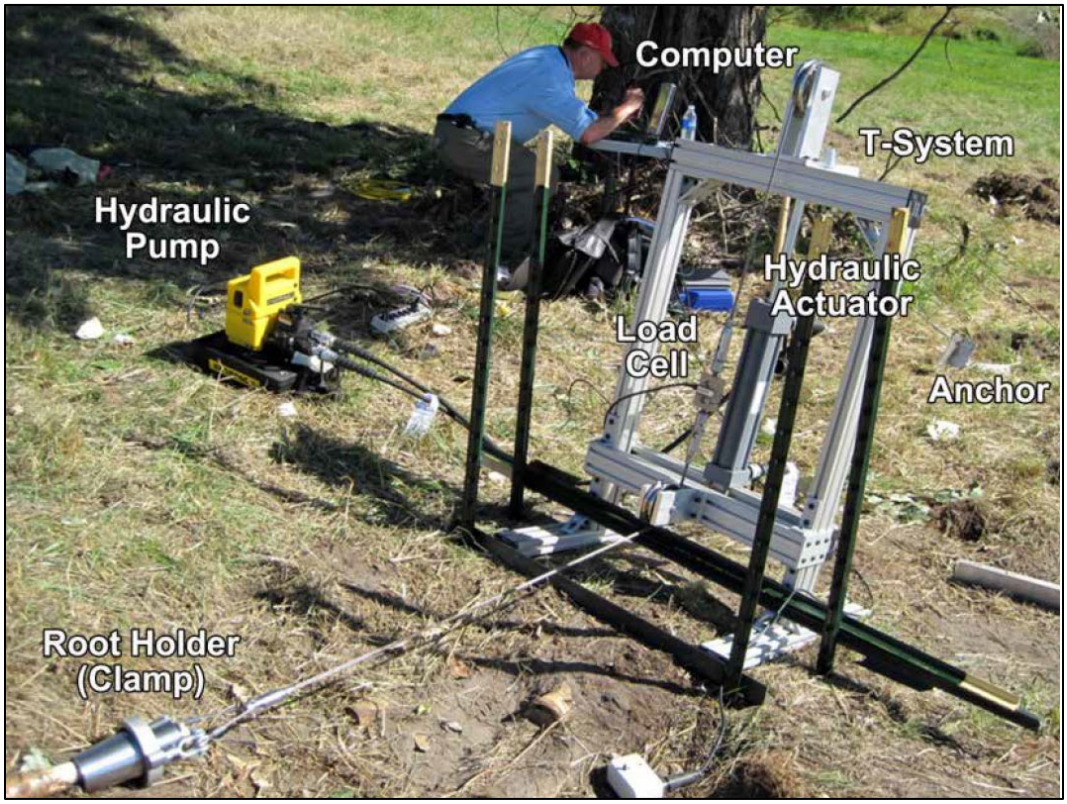
Abstract
Accounting for the influence of trees growing on and adjacent to levee slopes on slope stability requires information about the strength, size, and spatial distributions of tree roots. Spatial distributions may be addressed via root-architecture studies, while field and laboratory tests are used to measure root tensile and bending strength. One study of levee tree root strength involved conducting in-situ measurements of the strength of 55 tree roots from 17 trees growing on floodplains adjacent to levees at three sites. Tested roots measured 18–59 millimeters in diameter and had tensile strengths of 0.4 to 18 megapascals, slightly higher than indicated by a compilation of published tree root strength data that include regression relationships between tensile strength and root diameter for 11 riparian tree species. Inclusion of tree root effects in levee slope stability models has evolved from simple relationships between apparent cohesion and the root-area ratio, a measure of the fraction of the soil matrix occupied by roots to locally increasing soil strength in the vicinity of trees, to the use of fiber bundle models. Fiber bundle models have been shown to more accurately reflect reality; older approaches overestimate root contributions to soil strength and slope stability because they are based on the assumption that all roots break simultaneously.

4.1 Relevance to Levee Performance

One mode of levee failure is mass instability of the earthen embankment. Mass wasting or slope failure occurs when a large block of material slumps or slides out of the levee embankment. Because this type of soil loss makes the levee thinner and perhaps lower, it can accelerate seepage erosion or facilitate overtopping, and eventually lead to formation of a levee breach. Aboveground portions of vegetation can contribute to slope instability by adding weight and wind loads, but belowground roots can reduce slope instability by reducing soil moisture through evapotranspiration and direct reinforcement of soils when roots cross failure planes. An analysis of the effects of trees and their roots on slope stability (covered in Chapter 10, “Effects of Trees on Levee Slope Stability”) requires information about root strength as well as spatial distribution of roots. Root strength also figures into the resistance of trees to overturning under external loads from wind or water flows, but analyses of these types of treefall on levees have not included such detailed analyses to date (but see Coder 2010). For small roots, tensile strength is dominant, while large-diameter, structural roots have both tensile strength and bending resistance.

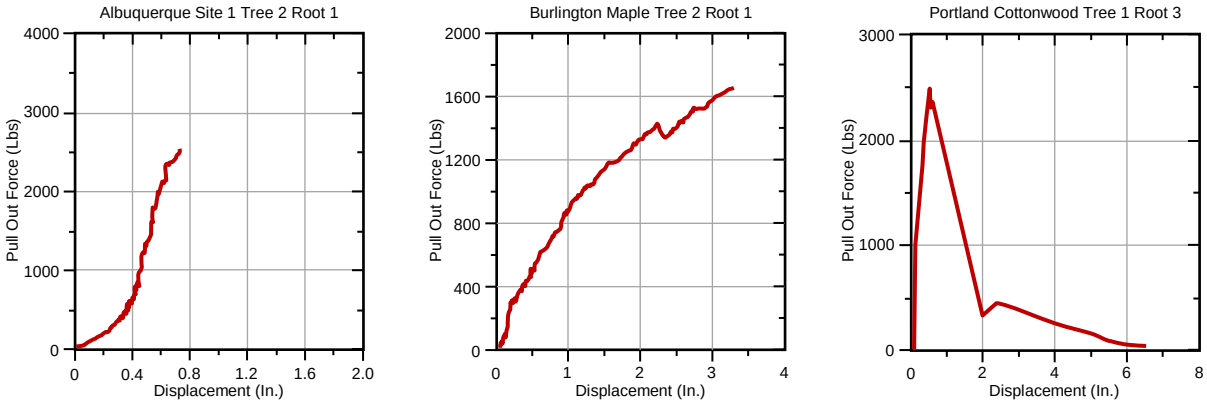
4.2 Root Strength Measurements

Root strength may be measured in situ using specially designed devices for pulling roots out of the ground and measuring the force required to cause “root failure” through breakage, stretching, pullout, or some combination of these. A system used by the USACE ERDC is depicted in Figure 4-1. Output from a single test conducted using such a system (Figure 4-2) consists of a graph of load (y-axis) versus displacement (x-axis), as measured by the load cell. Roots that



Sources: Wibowo et al. 2011, Wibowo and Corcoran 2012

Figure 4-1. Root Pullout System Used for Root Pullout Field Tests by USACE Engineer Research and Development Center



Source: Wibowo and Corcoran 2012

From left to right, failure modes are root breakage, root pullout, and a combination of the two modes. Curves on left and in middle show tests ended when displacement reached a critical value, but one may infer that roots broke or pulled out at this point and force dropped to zero.

Figure 4-2. Example Load versus Displacement Curve for Root Pullout Field Tests

snap (breakage failure mode) produce a curve that reaches a peak and abruptly drops to zero load at some critical displacement. Roots that fail by pullout produce curves that rise sharply and gradually flatten as smaller roots and root-soil bonds along the root network fail. Roots that fail with a combination of the two modes show an initial sharp increase in load, a sharp decrease to some nonzero residual level, and then a gradual decline. Some workers conduct pull tests by pulling the end of the severed root that is still connected to the tree, thereby forcing failure by breakage (Pollen-Bankhead et al. 2013). In all cases, the root strength is the load that corresponds to the peak of the load versus displacement curve. Most existing root-strength data of this type are for roots less than 70 mm in diameter.

The system depicted in Figure 4-1 was used by the USACE ERDC to test 55 roots from 17 trees representing five species at sites in Burlington, Washington; Portland, Oregon; and Albuquerque, New Mexico. Tested roots were not from trees growing on levee slopes, but were on the adjacent floodplain.

Larger diameter roots typically have greater absolute strength, but root tensile strength (the force required to pull the root out divided by the root cross-sectional area before pulling) decreases exponentially with diameter, perhaps because smaller roots have higher cellulose content (Genet et al. 2005). Many workers have fit power law functions to root tensile strength-diameter datasets in the form of

$$T_r = ad^b \qquad (1)$$

where T_r is the tensile strength, d is the root diameter, and a and b are regression coefficients.

Pollen-Bankhead et al. (2013) compiled coefficients a and b for a wide range of grass, shrub, and tree species, and an excerpt of their compilation featuring trees in North America is provided in Table 4-1. Hales et al. (2013) do not support the use of nonlinear regression formulas for tensile strength as a function of root diameter because tensile strength incorporates the diameter within the root cross-sectional area. They advocate using linear regressions of force at failure against root diameter instead of using root tensile strength.

Curves corresponding to the coefficients in Table 4-1 are depicted in Figure 4-3 along with data from Corcoran et al. (2011). Reported root tensile strengths are between 1 and 100 megapascals (MPa), with grass values between about 4 and 20 MPa and trees between 5 and 70 MPa. For small roots (less than 1 mm), grasses have the greatest tensile strength. Grasses may provide significant reinforcement to upper layers of soil where the density of fine, fibrous roots is high and increase factors of safety for shallow failure planes, such as those that occur in sandy soils of low cohesion (Shields and Gray 1992). Small roots that permeate a soil mass create a reinforcement that behaves as an “added cohesion” or “root cohesion” of the soil-root compound. Also, small roots have better capacity to exploit water in the soil, and thus, lower pore-water pressures. Woody plants provide greater soil reinforcement than herbaceous plants due to a wide range of root sizes over a wide range of depths. Larger tree roots tend to be stronger than for shrubs and grasses. They act as structural reinforcement in a same way as ground anchors or soil nails do. Data from Corcoran et al. (2011) include tree roots with diameters in the range of 18–59

mm with tensile strengths between 0.4 and 18 Mpa. These values appear to be slightly higher than values published by others for riparian trees.

Table 4-1. Power Law Function Coefficients for Root Tensile Strength-Diameter Relations, Fit to Data for Tree Roots plus Averages of Published Coefficients for Grasses, Shrubs, and Trees

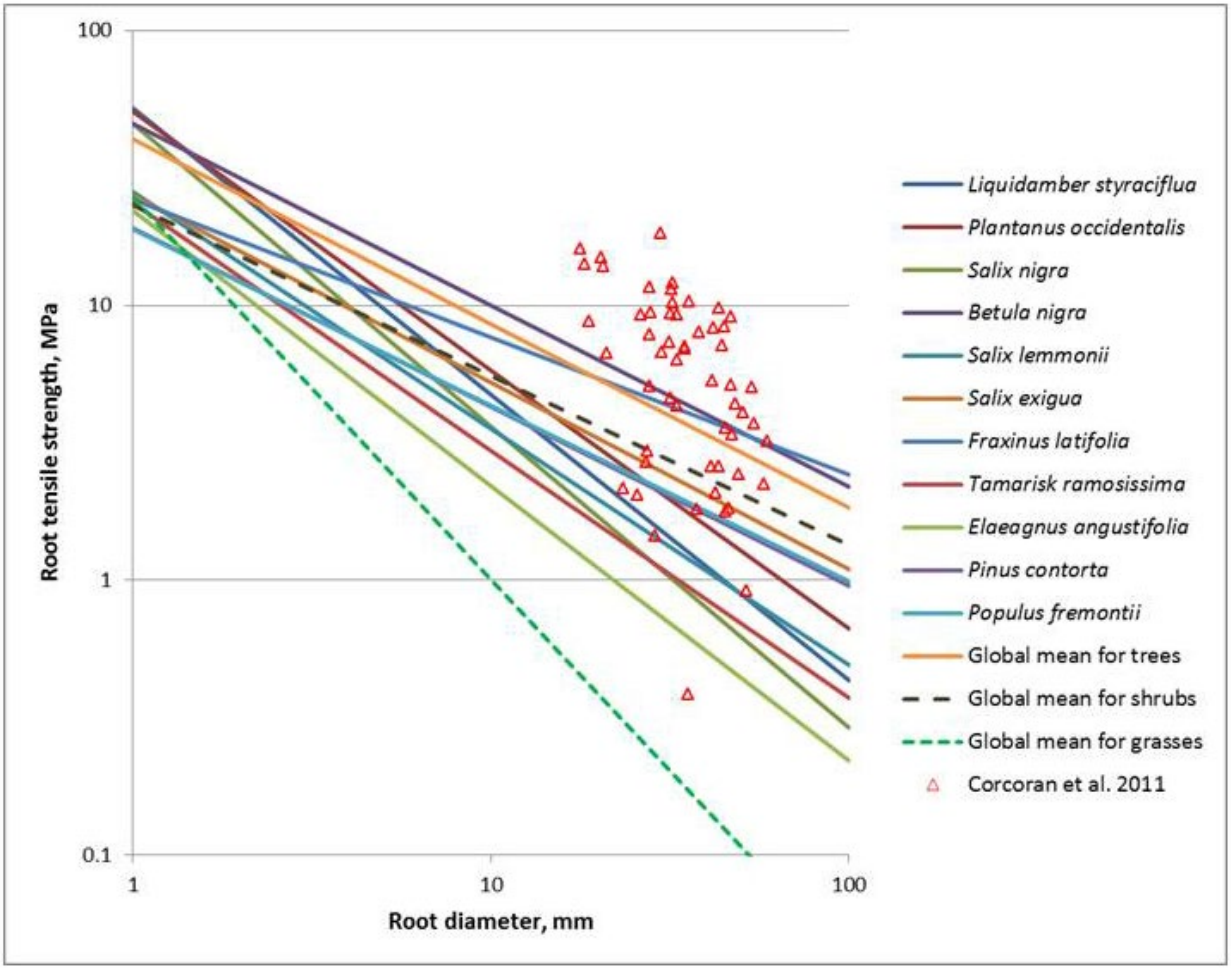
Species	Type	Location	a	b	Reference
Liquidambar styraciflua	Tree	Mississippi, USA	52.1	-1.04	Pollen and Simon 2005
Pltanus occidentalis	Tree	Mississippi, USA	50.5	-0.94	Pollen and Simon 2005
Salix nigra	Tree	Mississippi, USA	45.9	-1.1	Pollen and Simon 2005
Betula nigra	Tree	Mississippi, USA	45.8	-0.66	Pollen and Simon 2005
Salix lemmonii	Tree	California, USA	25.93	-0.86	Simon et al. 2006
Salix exigua	Tree	Kansas, USA	25.2	-0.68	Pollen and Simon 2005
Fraxinus latifolia	Tree	Oregon, USA	24.3	-0.5	Pollen and Simon 2005
Tamarisk ramosissima	Tree	Arizona, USA	23.6	-0.9	Pollen-Bankhead et al. 2009
Elaegnus angustifolia	Tree	Arizona, USA	22.1	-1	Pollen-Bankhead et al. 2009
Pinus contorta	Tree	California, USA	19.06	-0.65	Simon et al. 2006
Populus fremontii	Tree	Oregon and Kansas, USA	18.9	-0.64	Pollen and Simon 2005
Mean	Tree	Global mean	40.12	-0.67	Pollen-Bankhead et al. 2013
Mean	Shrub	Global mean	23.23	-0.62	Pollen-Bankhead et al. 2013
Mean	Grass	Global mean	24.72	-1.39	Pollen-Bankhead et al. 2013

Source: Pollen-Bankhead et al. 2013

Other workers have conducted tests of the shear strength of root-permeated soils in situ using shear boxes. Excavations are performed to isolate a cubical pedestal of root-reinforced earth, which is then sheared from its base using an apparatus that measures displacement and shear force (Mickovski and van Beek 2009, Mickovski et al. 2009). Still other workers collect root segments and return them to the lab and clamp them at both ends before subjecting them to tensile forces (Mickovski et al. 2009, Pollen-Bankhead et al. 2013). Perhaps the most common approaches to studying root effects on soil strength are based on laboratory tests of root-reinforced soil samples across a range of scales using either plantings grown in special containers (Mickovski et al. 2009) or soils impregnated by fibers that serve as idealized analogs of roots.

4.3 Root Contributions to Soil Strength

Because small roots (less than about 3.5 mm in diameter) are much more numerous than large ones (greater than about 50 mm), small roots make a significant contribution to soil strength. Further, some workers argue that larger roots tend to pull out of the soil rather than contribute directly to soil cohesive strength (Hales et al. 2009), and data from Corcoran et al. (2011) and



Source: Pollen-Bankhead et al. 2013 unless otherwise specified

Average values for grasses and shrubs from sites worldwide shown for comparison.

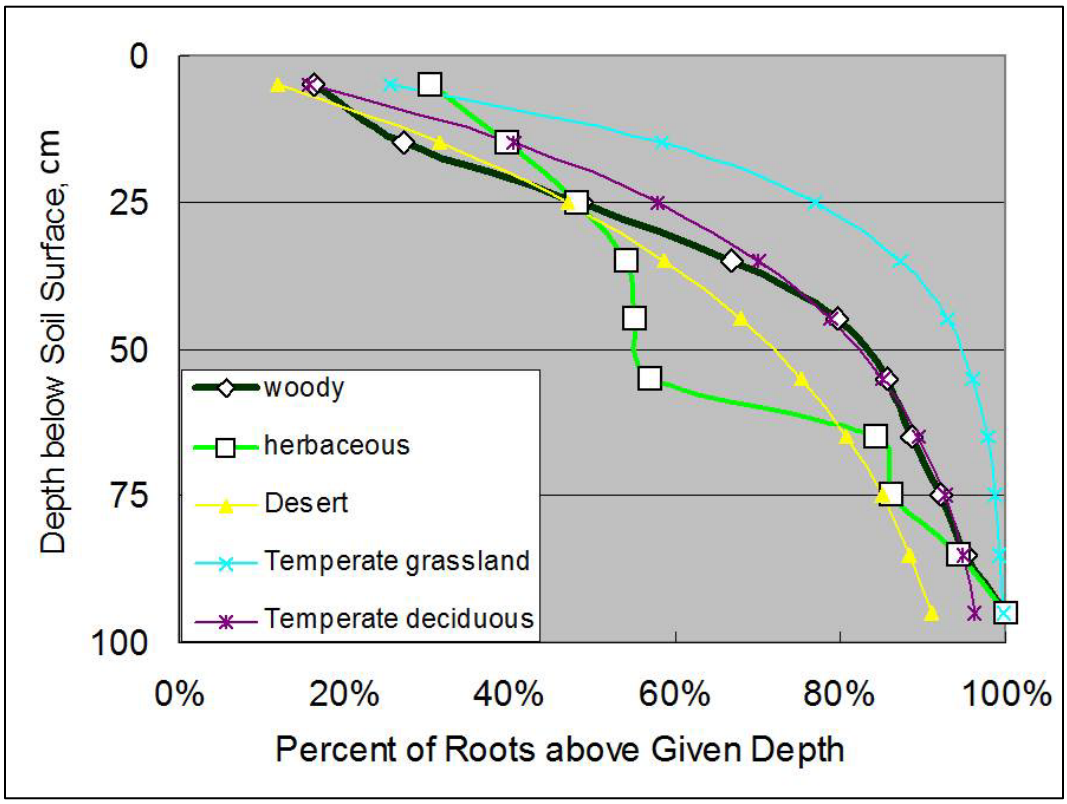
Figure 4-3. Selected Root Tensile Strength versus Root Diameter Relations for Tree Species in USA

Mickovski et al. (2009) are consistent with this hypothesis. Pullout occurs because the root itself is stronger than the soil/root bond. Furthermore, smaller roots may have more extensive branching, and thus, greater root-soil friction bonds, reducing pullout and increasing breakage. On the other hand, larger roots offer some resistance to bending. Fine roots have low bending stiffness, but coarse roots can resist both tensile and bending forces (Pollen-Bankhead et al. 2013).

In contrast to findings by Hales (2013) and Corcoran et al. (2011), Pollen et al. (2004) found that roots larger than about 2.4 to 3.5 mm (the threshold value depends on soil moisture [Pollen and Simon 2006]) almost always broke rather than pulled out of the soil, while smaller roots failed both ways. Perhaps from a root reinforcement standpoint, there is an optimum root diameter that represents a balance between small, weak roots and large roots that are susceptible to pulling out.

Among tree species, variations in root tensile strength tend to be small (Pollen et al. 2004, Hales et al. 2009, Corcoran et al. 2011), but significant variations occur among sites (Hales et al. 2009, Corcoran et al. 2011), perhaps because of site soils, topography, and microclimatic considerations that affect root cellulose content. Furthermore, the contribution of roots to soil strength varies with the size and distribution of roots and with their tensile strength. Simon et al. (2006) found that root tensile strengths for lodgepole pine and Lemmon's willow were similar, but the willow provided an order of magnitude greater root reinforcement to streambanks because of differences in root numbers and distribution. In another study, average root-reinforcement values for Russian olive and tamarisk were 2.5 and 3.2 kilopascals (kPa), respectively, while the tensile strength–root diameter curves for these two species were very similar (Pollen-Bankhead et al. 2009).

Although large and small roots are distributed differently, the density of all types of roots declines exponentially with depth below the surface (Pollen et al. 2004, Mickovski et al. 2009, Hales et al. 2009). Herbaceous plants tend to have shallower, finer roots (Figure 4-4). The rate of decrease of root density with depth is slower in highly permeable, droughty soils, but still occurs (Shields and Gray 1992). Accordingly, the contribution of roots to soil strength declines sharply with depth (Shields and Gray 1992, Mickovski et al. 2009).



Source: Shields 2007

Figure 4-4. Vertical Distribution of Numbers of Roots for Sites on Sandy Sacramento River Levees under Woody and Herbaceous Cover (Gray et al. 1991) and Typical Curves for Various Terrestrial Biomes from Jackson et al. (1996)

4.4 Mathematical Representations of Root Contributions to Soil Strength

Slope stability analyses require inputs describing the spatial distribution of roots and their strength to represent effects of woody vegetation. Slope stability analyses are described in Chapter 11, "Risk Analysis and Levee Vegetation," although this chapter focuses on root strength. When slopes are vegetated, roots that grow sufficiently deep to cross potential failure planes contribute to soil shear strength, and thus, affect slope stability. Engineers have used various methods to compute the additional strength that roots impart to the soil, but all methods depend to some degree on the known or assumed tensile strength of the roots, and the affinity of the roots for the soil in which they are embedded. An example of early work of this type is provided by Shields and Gray (1992), who simply assumed that roots contributed an "apparent cohesion" to soil shear strength that could be added to the base level of cohesion. They further assumed that apparent cohesion could be computed by multiplying the RAR (defined in Chapter 2 of this report) by a constant:

$$c_r = 0.23RAR \qquad (2)$$

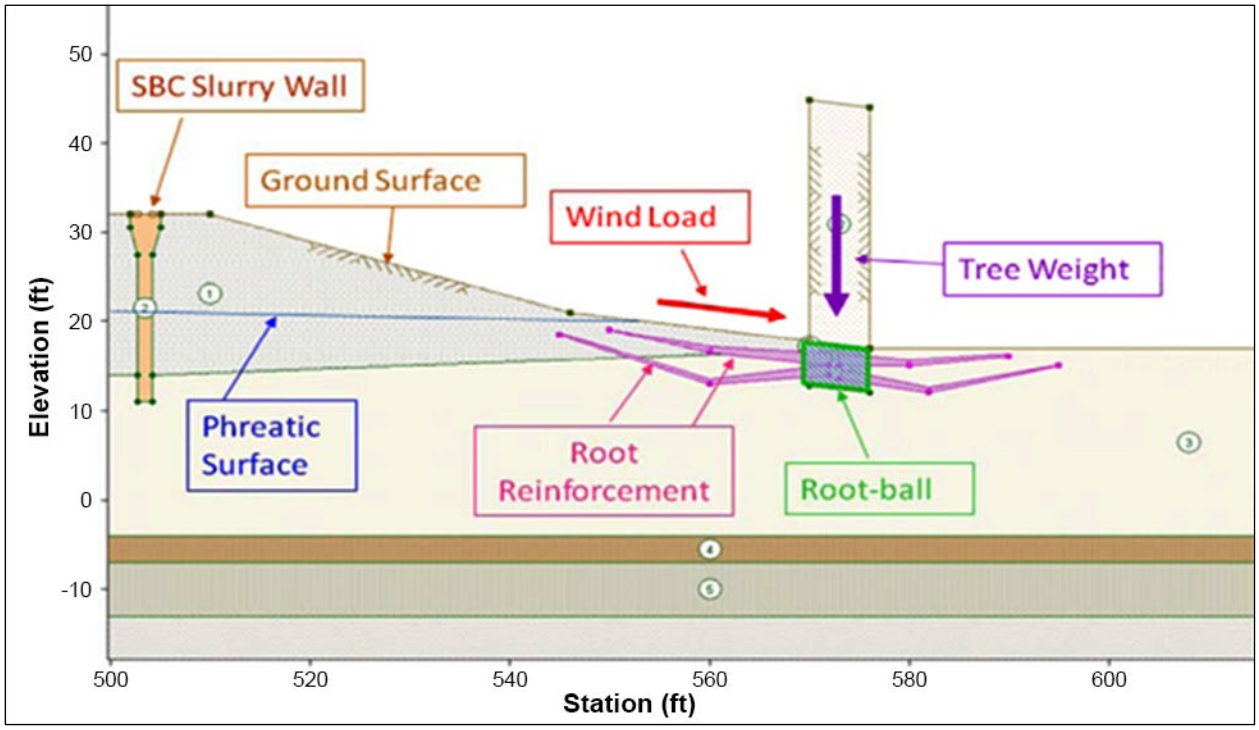
where c_r = soil shear strength (apparent cohesion) due to roots in kilograms (kg) cm^{-2}, and 0.23 = coefficient based on an assumed density for roots of 640 kg m^{-3} and the mean of published shear strength measurements and root biomass concentration for sand soils, and RAR = root-area ratio. This equation becomes

$$c_r = 22RAR \qquad (3)$$

for c_r in MPa.

This simple model has many shortcomings; for example, it assumes that all roots are perpendicular to the failure plane and tends to overestimate the contribution of roots to soil strength (Pollen et al. 2004).

Root contributions to soil strength were included in 2D slope stability analyses by Corcoran et al. (2011), which are reviewed in Chapter 10, "Effects of Trees on Levee Slope Stability." Harder (2012d) reported that the Corcoran et al. (2011) analyses represented root contributions in two ways. First, soil cohesion was increased inside a zone of assumed dimensions that represented the root ball: "Typical increased values of cohesion were about 50 psf [pounds per square foot] for sands and 100 psf for clays." Second, reinforcing elements were added to the region adjacent to the "root ball" element to represent large roots (Figure 4-5). Two "roots" were placed in the upslope direction from the tree location and two in the downslope direction. Individual root strength from field pullout tests was used for soil next to the tree, and then decreased to zero reinforcement at a distance of 15 ft. If the individual root was determined to have a pullout strength of 1,500 pounds, this was added to the soil strength next to the tree and linearly decreased to zero at a distance of 15 ft. To account for 3D effects, root strength was distributed over the width of the root ball (6 ft). Therefore, a strength of 250 pounds per linear foot per reinforcing element was assigned next to the tree, and this value decreased to a value of zero at 15 ft from the tree.



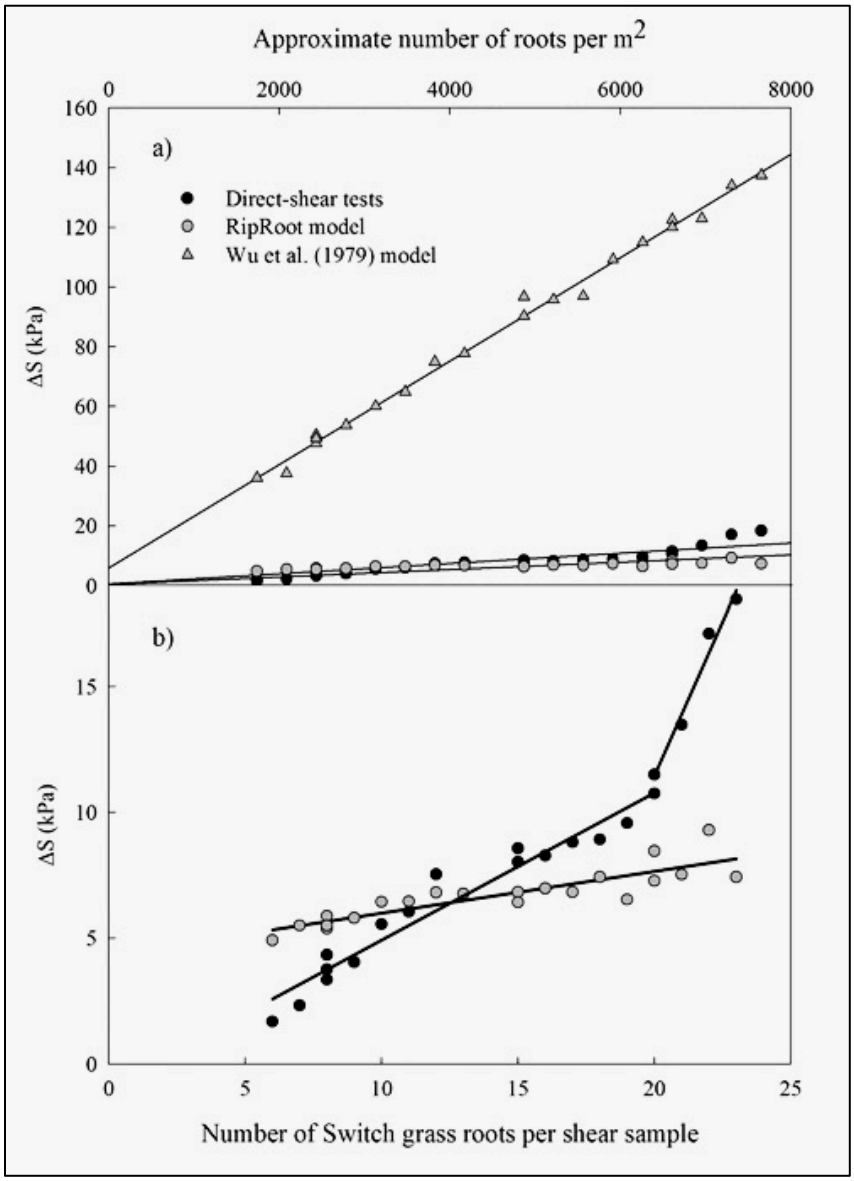
Source: Corcoran et al. 2011

Figure 4-5. Schematic of Approach Used by Corcoran et al. (2011) to Simulate Contribution of Roots to Soil Strength for Levee Slope Stability Analysis

Technology for analyzing root contributions to slope stability has been evolving. Newer analyses include information on species-specific relations between root tensile strength and root diameter, root size and spatial distributions, and influences of vegetation on soil moisture and matric suction (Mickovski et al. 2009, Pollen-Bankhead et al. 2009 and 2013). The most current methods of accounting for root contributions to soil strength rely on algorithms known as fiber bundle models (FBMs), which were developed by materials scientists to simulate fiber-reinforced materials. In contrast to older methods, which assume that the full strength of all roots is simultaneously imparted to the root-soil matrix and that all roots break simultaneously, the FBM allows for progressive breaking of roots. The FBM approach is dynamic and therefore requires simulation of time-varying phenomena with a model computation at every time step during a simulated period of load application. FBM output is used in equations for slope stability as the term that represents the root contribution to soil shear strength (Thomas and Pollen-Bankhead 2010), and this contribution is calculated at each time step in the dynamic simulation.

FBM algorithms require root strength information such as that derived from pullout tests described above and spatial distributions of roots. The FBM algorithms are set up to assign load to each root either equally (i.e., at every time step in the model, each intact root receives 1/N of force where N = number of roots) or in proportion to their cross-sectional area. The former approach results in smaller, weaker roots breaking first while the latter results in breakage of larger roots first. The first FBM approach is more consistent with observed behavior of root-reinforced soils, because the weakest roots tend to break first, and tends to give the best results

when compared to other approaches (Pollen and Simon 2005, Mickovski et al. 2009). It should be noted that FBM accounts only for root strength contributions to soil strength; the density and spatial distribution of roots in the soil (say, the number of roots of a given size per unit area of the failure plane) must also be provided to conduct slope stability analyses (e.g., see Figure 4-6). Additional detail regarding the FBM approach for slope stability analysis is provided by Pollen and Simon (2005) and Thomas and Pollen-Bankhead (2010).



Source: Pollen and Simon 2005. ΔS determined by direct shear tests, the RipRoot model (based on fiber bundle model), and the traditional approach for accounting for plant root contributions to soil strength (Wu et al. 1979).

Figure 4-6. Additional Soil Strength due to the Presence of Switchgrass Roots (ΔS) as a Function of Root Density (a) and a Detail of (a) Using a Constrained Axis to Show Only the RipRoot and Direct Shear Results

4.5 Data Gaps

Published data are for roots smaller than about 70 mm in diameter, and the strength and influence of very large, deep roots is less well understood. Clear-cut, scientifically defensible guidelines for representing the influence of roots in slope stability models, especially 2D models, are needed.

4.6 Points of Scientific Debate

Data on root strength are increasingly common in the literature, but extrapolation of data for a given species from site to site is problematic. Most controversial is the selection of an appropriate method for including the contribution of roots to soil strength in slope stability analyses. The FBM approach appears to provide the most realistic results, but it should be noted that some aspects of the FBM approach have been questioned (Mickovski et al. 2009). This topic is discussed further in Chapter 10, “Effects of Trees on Levee Slope Stability.”

4.7 Potential Implications for Levee Vegetation Management

Tree root tensile strength declines exponentially with root diameter, but strength for a given diameter varies across a relatively narrow band regardless of species. Several methods have been proposed for simulating the contribution of tree roots to soil strength in geotechnical slope stability models.

5 Root Decay and Levees

Abstract
Levees are sometimes damaged or fail due to internal erosion associated with water seepage known as piping. Pipe formation requires some type of void in the soil matrix, and some have argued that voids left by decaying roots may induce piping. Reviewed herein are several scientific studies both applied and theoretical regarding tree root decay in hillslopes and levees. Among these are four studies in central California that involved excavation into levees that revealed living, dead and decaying roots. Voids created by decaying roots were not found. Another study in France involved burial of root samples in levees and subsequent exhumation after definite periods of time to allow measurement of decay rates. Decay rates were found to be related to tree species and root diameter.

5.1 Relevance to Levee Performance

Voids are created in natural soils and soil structures by many processes (Gray 2013):

- Shrinkage cracks
- Hydraulic fractures
- Contact surfaces (e.g., compaction lift planes)
- Animal tunnels
- Relict root holes
- Soil pipes (from washout of fines through gap-graded soils)
- Manmade activities, encroachments, or penetrations

Large roots in levee embankments represent a discontinuity or nonuniformity in soil permeability or conductivity that may facilitate formation of preferential flow paths for seepage, and perhaps seepage-induced erosion, or piping (USACE 2014). It is important to note that Gray (1991) performed a comprehensive review of the literature on the subject and concluded that "[m]uch of the evidence with regard to the biotic origin and/or cause of pipes appears to be inferential or anecdotal in nature." This statement continues to hold true. This is not surprising, as failure of a levee embankment because of piping associated with decayed roots would likely destroy the roots, and the presence of roots within remnants of failed dams and levees is not conclusive evidence of causation. Advances in understanding how decayed roots influence water movement and attendant erosion in earthen embankments is likely to be based on the kinds of field-scale

and numerical experiments described in Chapter 9, “Effects of Trees on Seepage and Piping in Levees.”

Blocked tubular voids (pipes) running parallel to the slope direction can fill with standing water and generate soil pore-water pressures much greater than those generated by total saturation of the soil (Gray 2013), contributing to slope instability (Pierson 1983). Root-induced seepage might be worse for decayed roots that leave behind regions of very low density or voids as organic matter is oxidized (Day et al. 2010). The hazard of decayed roots would occur if trees were allowed to pass through their normal life cycle on levees, because roots and eventually the entire tree must die. On the other hand, tree removal may exacerbate root-induced seepage when removal is performed because dead stumps or substantial portions of the root mass are left behind. Removal of root balls or individual roots at the time of tree removal may be prophylactic, but is extremely costly and hard to do thoroughly (Buer et al. 2012). As noted by Zanetti (2010):

> If the growth of the roots is injurious for the safety of the hydraulic structural work in embankments, the felling of trees and the death of the stumps generate even more significant risks: effectively, the decomposition of the roots and stumps create… low density zones, even voids, in the dike body.

The focus of this chapter is recent research relevant to the topic of tree root decay in and adjacent to levees. The rate of root decay and the propensity of decaying roots to trigger void formation in levee soils are of interest; seepage induced by living and dead roots is considered in Chapter 9, “Effects of Trees on Seepage and Piping in Levees.”

Abundant work has been performed measuring and modeling the impacts of forest clear-cutting on slope stability (e.g., Sidle 1992). Although it is important to note that the hydrology of hillslopes (loading from precipitation and runoff from upslope) is intrinsically different from that of levees (flooding from toe upward on waterside face), forest slope studies are useful. Landsliding increases dramatically following timber harvest from steep slopes (Reid and Keppeler 2011) because of the loss of root reinforcement as roots decay (Vergani et al. 2013), and subsurface flow increases as decayed roots provide flow paths for infiltration, seepage, and piping (Ziemer 1992, Beven and Germann 2013). Such flow often occurs through macropores (channels greater than 30 micrometers [μm] in diameter), which can be of significant size (Leslie and Heinse 2013).

Although networks of connected, continuous macropores obviously create conditions for the most rapid movement of water, networks of discontinuous macropores also greatly accelerate flows in slopes (Nieber and Sidle 2010). Lammeranner et al. (2007b) argue that the death of a single tree on a densely vegetated slope has effects quite different from those of clear-cutting, because zones occupied by dead roots are quickly occupied by a new generation of roots from surrounding trees. Thus, slope stability is not adversely affected by the root death of a single tree in a stand, because in a dense stand or grove the live roots will intermingle and intersperse with dead roots.

5.2 Qualitative Observations

Gray et al. (1991) conducted profile wall excavations to expose roots in stands of herbaceous vegetation, along the driplines of four species of trees, and through the middle of a clump of elderberry bushes. Excavations were conducted on sandy levees on the west bank of the Sacramento River just upstream from Sacramento in 1986. Voids caused by insect or animal activity were frequently encountered, but "no voids clearly attributable to decayed or rotted roots were observed." In a few cases, root bark layers ("castings") were encountered that were filled with soil (sand); these were termed "pedotubules" (Figure 5-1). Additional excavation around an oak stump showed a taproot of 0.5 m in diameter at 1.4 m below the levee surface, with lateral roots of 0.1 m still intact after more than 20 years of decay.

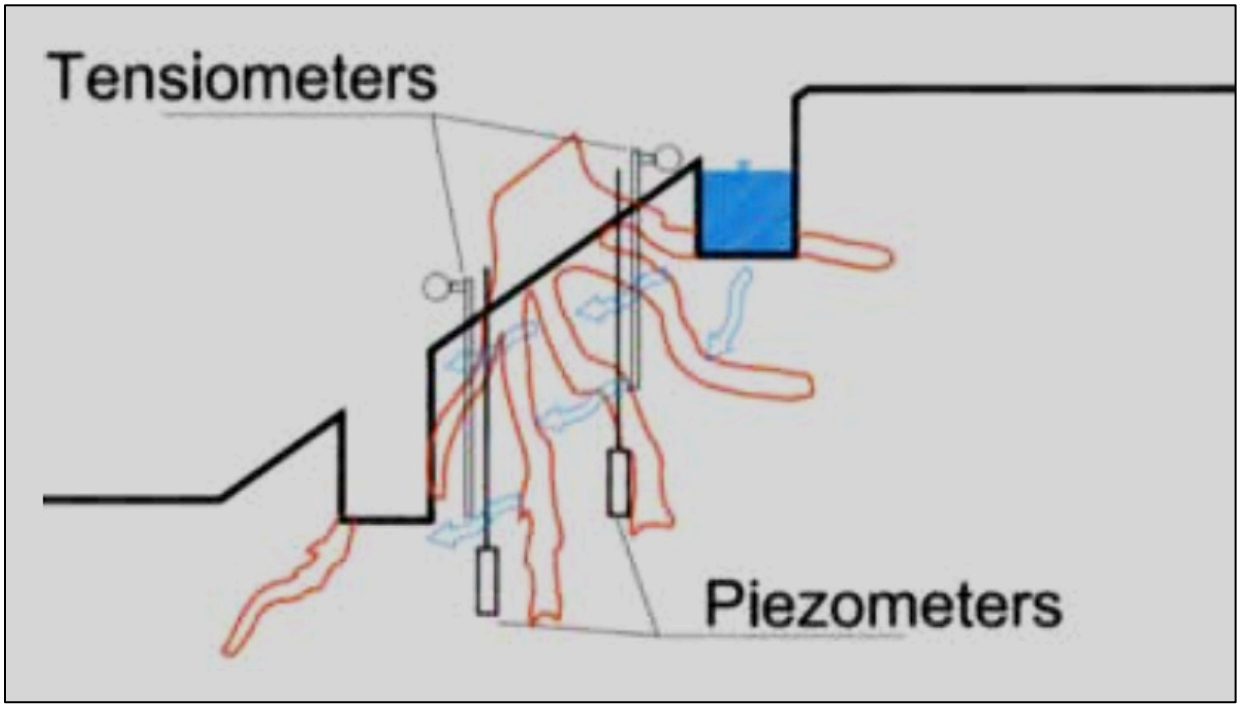
Source: Gray et al. 1991

Root bark has formed a cast filled with sandy soil. When casting was broken by profile wall excavation, sand spilled out.

Figure 5-1. Relict Root Exposed in Profile Wall Excavation, Sacramento River Levee, 1986

Harder et al. (2011) conducted manual excavations to expose roots in the vicinity of a soil cement bentonite cutoff wall in a Sacramento River levee in the Pocket area in 2009. Large trees were growing on and adjacent to the levee, and roots were frequently encountered in the excavations. The investigators concluded that construction of the cutoff wall (in 1991) cut or broke several roots, which ranged in diameter from 0.25 to 4 in. Some of them were dead but only partially decayed. No evidence of void formation promoted by root decay was reported.

Shriro et al. (2011, 2012) reported excavation of trenches in a levee in the Sacramento area that were on the landside levee slope, running parallel to the levee centerline and upslope and downslope from a dead, decaying eucalyptus stump that was likely planted in 1964 and cut in 1993, or about 17 years before the study. Partially decayed roots were frequently encountered. The upper trench was filled with gravel and then loaded with water to conduct a "wetting test" (Figure 5-2). Similar testing was conducted on the same levee slope a short distance away, where the slope was free from trees and stumps. Movement of water downslope was monitored using a network of tensiometers.



Source: Shriro et al. 2012

Figure 5-2. Simplified Schematic of Field Test Described by Shriro et al. (2011)

During the wetting test, no evidence was observed of water traveling in the decomposing root system (M. Shriro, personal communication 2015). Instead, water movement was dominated by flow through a network of shallow mammal burrows, and flow through the region containing the stump was slower than for adjacent areas under only herbaceous cover; the area below the stump was the last to saturate during the wetting test.

Zanetti et al. (2011a, 2012) stated that decaying roots pose a danger of void (or "gallery") formation in levee embankments. Empirical support for this statement was limited to a single photograph of a root-induced void (Zanetti et al. 2011a). A similar void is shown in Figure 5-3. Consistent with reports by Gray et al. (1991), Zanetti et al. (2011a) reported that roots decaying in noncohesive soils did not leave behind voids, as soils gradually filled the spaces occupied by roots, but that voids associated with decaying roots were found in cohesive soils.

Source: Zanetti et al. 2012

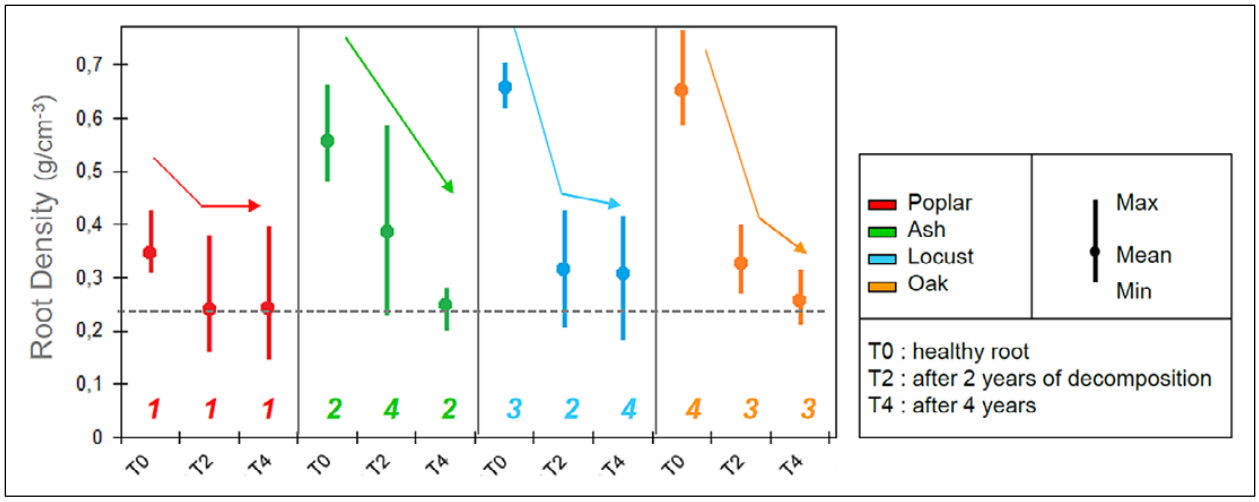
Figure 5-3. Void in Silty/Cohesive Soil Caused by Decayed Root

5.3 Measured Data

Zanetti (2010) and Zanetti et al. (2012) reported the results of an experimental study to measure effects of root decay for tree roots in French flood-control levees. Tree root cuttings (samples) of four species (oak, ash, locust, and poplar) were buried at 50 cm depth in wire cages on French levees. Root samples were 20 cm long and of five diameter classes (2, 3, 5, 8, and 10 cm). A total of 380 samples were obtained and measured (length, diameter, and weight) before burial, and subsets of the buried roots were exhumed and measured again after 2 and 4 years of burial, with another subset scheduled for exhumation in 2014. Forty samples representing four species were scanned for density using X-ray tomography at 2-year intervals. Loss of density was found to depend on root diameter (small roots decay faster) and species (Figure 5-4). Additional work by this same group includes ongoing experiments with three coniferous species (C. Zanetti, personal communication 2014).

5.4 Data Gaps

Additional observations of dead roots and their decay rates in levee embankments would be interesting, as would measurements of water movement through animal burrow–free embankments with and without decayed tree roots. However, the wide range of uncontrolled variables (soils, tree species, antecedent weather, flood history, animal activity) would make it very difficult to generalize observations from one or a few sites to the regional or national scale.



Source: Zanetti et al. 2012

Integers in colored font above the x-axis indicate the relative rank of each species for the given time, with 1 being least dense and 4 being most dense. For example, at time 2 (2 years), poplar had the lowest density while ash was most dense.

Figure 5-4. Loss of Density following Burial of Tree Root Samples for Four Species

5.5 Points of Scientific Debate

There is controversy regarding how serious a threat to levee integrity is caused by void formation caused by root decay, relative to voids created by other processes. Reports of voids associated with roots are scarce, and such voids tend to be discontinuous and relatively small, while much larger and longer tubular voids associated with mammal burrows have been observed in levees. Additional voids have been detected that are associated with other processes listed in Section 5.1 above.

5.6 Potential Implications for Levee Vegetation Management

There is consensus that tree roots decay after trees die or are cut down, and that the decay rate varies with soil properties, tree species, and root diameter. Substantial decayed roots may occur for decades after tree death. Decaying roots have been reported to create tubular voids in cohesive soils. There have been no reports of decaying roots creating tubular voids in sandy soils. Some workers note that the death of an individual tree on a levee slope creates a different impact than the death of a tree in a stand or group of trees because living roots rapidly colonize zones of decaying roots. Removal of all trees from an embankment supporting stands or groups would obviously not permit this colonization behavior. Decaying roots and the voids created by root decay may facilitate water movement in and through the soil profile, but decayed roots have not been implicated in pipe formation or growth in levees other than by anecdote. The significance of seepage associated with roots is examined in Chapter 9, “Effects of Trees on Seepage and Piping in Levees.”

6 Water Erosion of Levees

Abstract
During floods, levee waterside slopes may be threatened by erosion from river currents or waves. Levee crests and landside slopes may be eroded if the embankment is overtopped by waves or by the flood surge. Three published studies relate empirical observations of levee failure rates along the Missouri River to the width of waterside forest stands while one laboratory flume study quantifies effects of four woody riparian species on floodplain soil erosion rates. Trees were found to counteract but not eliminate fluvial erosion. Studies of overtopping erosion include forensic assessment of 41 tree-root-penetrated levees in the Midwest following the 2008 flood. There was no evidence that the roots had an impact on levee performance. One author presents analysis of a hypothetical case of local scour around the root ball of an overturned tree on the waterside of a Sacramento River levee. Maximum local scour was not great enough to compromise slope stability. Recent and ongoing laboratory tests are quantifying the capacity of grasses and herbaceous plants to provide protection to levee slopes from waves (waterside) and wave overtopping (landside). Field observations reported by two Chinese investigators indicate that strips of herbaceous vegetation or small trees protected levees during hurricane events. Additional ongoing laboratory research is likely to generate standard approaches for assessing beneficial effects of waterside vegetation on hydraulic loading from waves.

6.1 Relevance to Levee Performance

This chapter deals with surficial erosion issues; subsurface erosion, or piping, is covered in Chapter 9, “Effects of Trees on Seepage and Piping in Levees.” Earthen levees may be threatened by water erosion during periods of normal river stage as well as during floods, and vegetation growing on levee slopes may have positive and negative impacts in both cases. During normal river stages, levees may be subjected to minor, chronic erosion caused by rainfall, and slopes may exhibit sheet erosion or rill development caused by raindrop impacts or overland flow. Levee embankments may experience more serious chronic threats from wave wash erosion caused by wind- or vessel-generated waves. During floods, levees are subjected to fluvial erosion from shear forces created by river flow; local scour associated with flow past structures, trees, or any other type of obstruction; and erosion of the landside slope and levee crown by overtopping flows. Overtopping flows may be continuous, as when river stages exceed levee crest elevations, or periodic when waves break over the levee.

Woody vegetation (trees and shrubs) may reduce erosional threats to the levee by damping waves, reducing near-surface flow velocities and thus shear forces, and reinforcing and binding soils. The 1949 version of the Operations and Maintenance Manual for the Sacramento River Flood Protection Project allowed retention of “brush and small trees on the waterward slope where desirable for prevention of erosion and wave wash.” Further, it directed “where practicable, measures shall be taken to retard bank erosion by the planting of willows or other suitable growths on areas riverward of the levees.” On the other hand, woody vegetation may exacerbate erosion by concentrating flows between tree trunks or clumps of vegetation, creating

opportune sites for local scour (such as pits created by root balls removed by windthrow), or by suppressing turf development by shade.

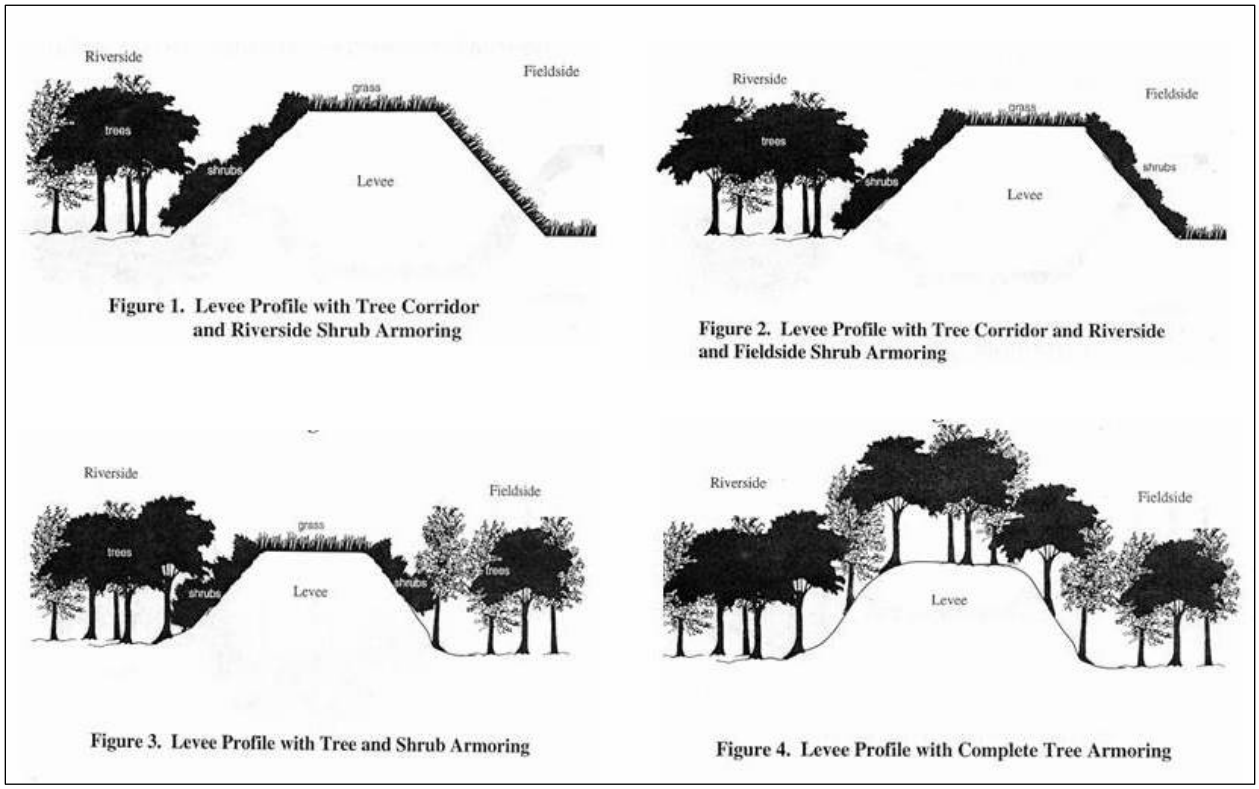
6.2 Impact of Woody Vegetation on Fluvial Erosion by Currents

Chen et al. (2009) conducted studies using the large flume of the J. Amorocho Hydraulics Laboratory at the University of California, Davis, that tested multiple depths and velocities of flows on four species of flexible stem riparian plants native to California and for bare soil (River Partners 2014). Examination of data in Chen et al. (2009) showed that mean soil erosion for bare surfaces ranged from 0.31 to 0.88 in and averaged 0.6 in, while erosion of vegetated surfaces subjected to similar hydraulic loading for test runs of several hours ranged from 0 to 0.61 in and averaged 0.20 in. The test flume had a flat bed that was 4 ft wide and supported flow depths up to about 5.5 ft and cross-sectional average velocities of 0.8 to 5.2 ft per second. These conditions are similar but not directly comparable to those found on waterside levee slopes during floods. Furthermore, wave wash erosion was not simulated.

Surveys of bank erosion along channels of the West Sacramento Levee System, which are closely bordered by levees, have noted vegetation as both an indicator of bank stability and a stabilizing, protecting influence (Rood and Howard 2008). However, erosion and woody vegetation sometimes occur together along eroding banks of the Sacramento River Flood Control System (USACE 2012). Design of new erosion controls for this system typically includes measures to protect existing riparian vegetation or to plant and foster its development to take advantage of its ability to damp waves and reduce fluvial stresses adjacent to bank sediments (e.g., Rood and Howard 2008).

Dwyer et al. (1997) and Allen et al. (2003) presented empirical evidence of the association between woody-corridor width and levee failures along the Missouri River in Missouri during the flood of 1993. Eighty-three percent of the levee failures occurred where levees were unprotected by woody vegetation or where the vegetated band between the levee and the river was less than 500 ft wide. Wallace et al. (1994) reported observations of levees in the same region following the same event: "…indicate that levees ….with woody vegetation cover on the levees may have saved many levees from damage and reduced the severity of damage to many others." Accordingly, they proposed for study four concepts for armoring levees with plant materials (Figure 6-1). Each concept consisted of prescribed blends of grass, shrubs, and trees for levee slopes and crowns and contained management provisions such as cutting frequency. As shown in Figure 6-1, armoring concepts included planting of trees on both sides of the levee and sometimes over the entire footprint of the levee.

Considerable recent research has examined the effect of various types of vegetation on velocity profiles, bed shear stresses, and sediment transport, and reviews are presented by Curran and Hession (2013) and Vargas-Luna et al. (2014). Although several formulations have been presented for computing the contribution of plants to flow resistance, much work remains to be done to compare and validate these models, particularly for application in hydrodynamic and sediment transport models of leveed floodways. Primary interest has been in assessing the effects



Source: Wallace et al. 1994

Figure 6-1. Vegetative Levee Protection Design Concepts Proposed for "Trial Use and Study on Midwest Levee Systems"

of nearly uniform vegetation on boundary shear and sediment deposition rates; more complex simulations of floodplains where both local scour and deposition are occurring in response to spatially varying densities of vegetation are emerging. Work by Manners et al. (2013) in assessing spatial variation of hydraulic roughness across a floodplain with varying vegetation properties is notable.

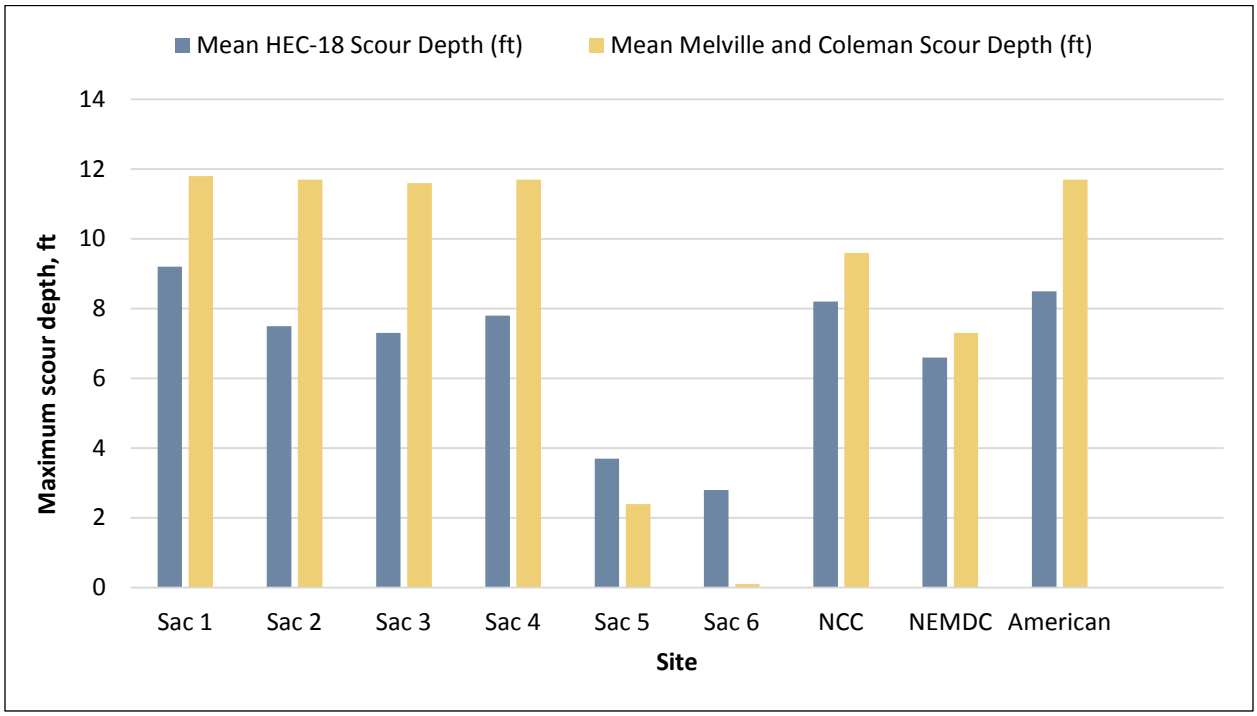
6.3 Impact of Woody Vegetation on Local Scour

Acceleration of flows around widely spaced or isolated rigid vegetation can produce local scour. Reports of such scour are limited and anecdotal. Models are available to predict local scour at bridge piers, and these have been adapted for estimating scour at tree trunks (treating them as erect cylinders) or at the root plate or root ball of overturned trees.

Rood et al. (2010) presented very conservative[7] calculations predicting the effect of scour around the root plate of large overturned trees (root wad 12 to 15 ft high by 2 to 3.5 ft wide by 12 to 15

[7] Rood et al. (2010) stated, "It is our view that all the maximum scour depths computed in this report are conservative and overestimate the actual scour that is likely to occur."

ft long) on the waterside of levees during a 200-year flood for selected locations along the Sacramento River that were part of improvements proposed for the Natomas perimeter levees (Figure 6-2). Uncertainties in hydraulic parameters, soils characteristics, and other inputs were handled via Monte Carlo analysis. Computed maximum scour depths ranged from 0.1 to 17.9 ft. Levee cross sections modified by scour erosion were then subjected to stability analysis under sudden drawdown. These analyses showed that all levee sections were stable for the maximum simulated erosion.



Source: Rood et al. 2010

ft = feet; NCC = Natomas Cross Canal; NEMDC = Natomas East Main Drainage Canal. Results are specific to soils, levee geometry, tree geometry, and hydraulics of each site.

Figure 6-2. Average of Local Scour Depths Adjacent to Fallen Trees on Levees Computed from Two Equations Using Monte Carlo Simulations for Nine Sites along Levees in the Sacramento, California Area under the 200-Year Flood Event

6.4 Impact of Woody Vegetation on Erosion under Overtopping Flows

Harder et al. (2008) reported inspection of 14 levee systems in the Midwest following the 2008 flood. Twenty-two levees breached, mainly by overtopping, while another 19 locations of levee overtopping without failure were reported. Long reaches of grass-covered levee performed well despite being overtopped by up to 2 ft of floodwater, an observation that was developed in greater detail by Bernhardt et al. (2011). Two breaches of the Mississippi River levee within the Cap au Gris Levee and Drainage District, 3 miles northeast of Winfield, Missouri, exposed tree roots as large as 18 cm in diameter that penetrated much of the levee embankment. Roots

apparently played no part in the levee failure. Harder et al. (2009) noted, "… [the] levee system was found to have extensive penetrations by tree roots that were revealed in breached sections, yet the levees performed well without problem up until they were breached by overtopping flows, and there was no evidence that the roots had an impact on the performance of the levee."

Several authors report flume tests of the resistance of grass-covered slopes or slopes protected with reinforced turf (grass growing through a mesh or wire screen) against erosion by overtopping flows or waves (e.g., Dutch studies reviewed by Corcoran et al. 2010, Steendam et al. 2010, Johnson 2011, Pan et al. 2013, Thornton et al. 2011 and 2012). These tests simulate erosion of landside levee slopes. For example, large-scale laboratory tests of slopes subjected to wave overtopping at Colorado State University revealed that stands of living Bermuda and Bahia grass protected slopes quite well, but that similar hydraulic loads caused significant erosion of bare clay or slopes protected with dormant grass (Figure 6-3 and Thornton et al. 2012). Prototype levees protecting coastal areas from storm surges in northern Vietnam were subjected to wave-overtopping simulator tests of 1–4 hours duration and specific discharges of 0.010 to 0.120 m^2 per second as described by Le et al. (2012). Most tested areas were protected by Bermuda or Vetiver grass cover of varying quality, but a few slopes also supported small (1- to 7-cm-diameter) *Casuarina* sp. trees. Local scour was observed adjacent to tree trunks, with catastrophic removal of an isolated 7-cm-diameter tree, leaving a root pit measuring 3 m in diameter and 1 m deep in the waterside slope of a levee built with "sandy clay."

Similar studies have been conducted at Colorado State University for various species of grass and reinforced turf under steady overtopping flows, but the results have not been published in the open literature because the sponsors were manufacturers of erosion control products and the data were proprietary (B. Scholl, personal communication 2013). A planned, prototype-scale test of overtopping flow erosion of levee slopes protected by a dense stand of shrubby willows was mentioned by Lammeranner et al. (2009a), but these experiments have not been conducted as of this writing (W. Lammeranner, personal communication 2013).

6.5 Impact of Woody Vegetation on Wave Wash

Protection of the watersides of levees subjected to frequent waves such as along the Mississippi River below New Orleans (Hertzberg 1954) or the Sacramento–San Joaquin Delta (Delta) (Whitlow et al. 1979, 1984) with plants or plant materials has been attempted with mixed results over many years. Whitlow et al. (1979) stressed the importance of structural toe protection (rock) and careful selection of plant species and propagation methods to match the vertical gradients that occur as a result of tidal flux and flow variations. Empirical and laboratory studies highlight the value of woody vegetation as a shield between the erosional processes typical of the main channel and the levee waterside slope. Markle (1979) simulated the effect of uniform stands of cottonwood trees, growing on the foreshore or berm between the lower Mississippi River main channel and the levee toe, on wave heights using physical scale models comprising rigid cylinders. He found that the trees reduced wave heights by 8% to 45%. However, the higher levels of attenuation required bands of trees that were 300–460 ft wide (measured perpendicular to the river and levee). Flexible parts of the trees (i.e., foliage) and undergrowth were not

(a) Metal tray with layer of pea gravel covered with geotextile.

(b) Tray similar to (a) with levee soils before compaction.

(c) Prepared trays in greenhouse with Bermuda grass turf growing on levee soils.

(d) Trays undergoing testing in wave overtopping simulator.

Source: (a), (b), and (c) are photos by author. (d) Courtesy C. Thornton, Colorado State University

Figure 6-3. Laboratory Facilities for Testing Vegetative Protection of Landside Levee Slopes Subjected to Wave Overtopping, Colorado State University

simulated. Sherman et al. (2007) reported results of studies of levee erosion caused by boat wakes in the Delta. Levees protected with woody vegetation were vulnerable to erosion, but brush bundles (a biotechnical erosion protection measure) reduced approximately 60% of boat wave energy incident on banks, and tule stands reduced wave energy by 15% to 30%.

Huang and Yu (2007) reported two cases from China where vegetation growing on berms or beaches on the waterside of levees greatly reduced wave damage during severe hurricanes. Lu et al. (1996) reported that a 10-m-wide strip of the wetland grass *Spartina alterniflora* about 1.5 to 2.5 m high reduced wave energy by 50% and that a 20-m- to 200-m-wide strip protected a levee from destruction while an adjacent levee segment without *Spartina* was "almost completely destroyed." A levee adjacent to a lake protected by "4 rows of pines of ~4 to 5 m height" protected a 600-m-long levee segment during a severe hurricane with a 50-year tide event, while adjacent sections without vegetation were severely damaged (Huang 2004).

Official guidance has been provided by the U.S. Department of Agriculture (USDA) Soil Conservation Service (now Natural Resources Conservation Service) (USDA 1974, 2014) for using a vegetated berm to protect embankment dams from wave wash erosion, but almost all of the guidance focuses on the use of herbaceous species. Ongoing laboratory wave-tank studies at the USDA Agricultural Research Service National Sedimentation Laboratory have produced considerable advances in understanding and predicting how stands of herbaceous, wetland vegetation attenuate waves (Ozeren et al. 2014). Wave-tank testing has included experiments with rigid and flexible model vegetation as well as real, live vegetation. Results from rigid model vegetation might be used to infer how very dense stands of woody vegetation would attenuate waves. For example, runs with a 4-m band of emergent vegetation achieved wave height attenuation of 40% to 60%. Similar laboratory work more strongly targeted at flood-control levees protected with turf reinforcement mats, woven geotextiles, and concrete armor units was reported by Johnson (2011).

6.6 Data Gaps

Standard approaches for assessing the beneficial impacts of waterside woody vegetation on wave wash either are available or will be shortly. However, such guidance for assessing the beneficial effects of various sizes and densities of woody plants on direct current erosion and erosion from overtopping are not available. Standard approaches for computing local scour (such as at bridge piers) should be quantitatively evaluated for application to erect trees, blocks of trees, or overturned trees (root balls) on levee slopes.

6.7 Points of Scientific Debate

Exposure of roots in failed levee embankments has been variously interpreted: roots either mitigated, triggered, or played no role in failure. Well-accepted approaches for weighing the beneficial impacts of woody vegetation on erosion potential against undesirable impacts are not available and must be addressed through subjective professional judgment. For example, if trees

on slopes reduce wave energy during the project flood by 50% but increase local scour potential at certain locations by 10%, how should these effects be compared? Because vegetation is subject to disease, decline, and death, how should variable future conditions of vegetation be assessed?

6.8 Potential Implications for Levee Vegetation Management

Woody vegetation growing at or riverward of the levee waterside toe can provide significant benefits in damping waves and reducing associated erosion during high water. When waterside berms are large enough to support floodplain forest, levee failure rates may decrease, presumably because the vegetation protects against direct attack by currents. Local scour around individual trees or blocks of vegetation is subject to site-specific controls such as the duration of flooding, the erodibility of the underlying soils, and the magnitude of local velocities. Effects of local scour on levee reliability are highly dependent on site-specific variables. Additional study would be needed to develop reliable models of impacts of vegetation related to local scour. Laboratory studies of slopes protected by turf and by reinforced turf subjected to flows similar to those created by levee overtopping have been completed, but similar data describing the performance of slopes protected by woody plants are not presently available.

7 Hazards to Levees from Treefall

Abstract
Trees growing on or immediately adjacent to levees create pits when overturned and uprooted by forces generated by wind or water flow. Research approaches include measuring forces required to pull over living trees using mechanical winching systems, although forces exerted on trees by such systems do not exactly replicate the dynamism of wind loads. Described here is one study that included winching tests of valley oaks and cottonwoods growing on levees in California's Central Valley. Forces (moments) required to topple trees were directly proportional to tree size, as were the areas of pits left by overturned trees. These results were consistent with findings by scientists working in other regions. The same study also included estimation of forces imposed on trees by winds and found that wind speeds large enough to generate such forces are rare in the Central Valley. Two studies described below include compilations of data on root pit size for overturned trees, with some overlap between datasets used in the two studies. Both studies produced regressions for pit size in terms of tree diameter at breast height. The regression curves produced pit diameter estimates of 2.1 and 2.4 m for a diameter at breast height of 0.5 m.

7.1 Potential Impacts of Treefall

The term "treefall" as used here refers to the overturning of a tree with most of its larger roots intact, thereby pulling much of the root mass and associated soil (or rootwad) out of the ground. Treefall is also referred to in the literature as tree uprooting, windthrow, tree tip, and other terms (Robbins et al. 2014). Pits created when trees are uprooted by wind or water flow represent removal of material from the levee prism or from the toe, shortening seepage paths. For example, Duncan (1999) reported the results of a SEEP/W simulation of sandy perimeter levees ("dikes") around Cross Lake, Minnesota. Seepage effects of large pits or holes created in embankments by uprooting of trees was assessed. Even pits as large as 5 ft deep and 60 ft wide on upstream (waterside) slopes had essentially no effect on the magnitude of the hydraulic gradient at downstream (landside) seepage exits. However, pits located at the landside levee toe and measuring 4 ft deep, 20 ft wide at the top, and 12 ft wide at the bottom increased hydraulic gradients from 0.93 to 1.22, increasing the risk of erosion and piping.

Pits located on or near the crest of small levees might be large enough to reduce freeboard if enlarged by scour. Root pits may be enlarged by local scour if trees are uprooted on the waterside during a flood. Levee embankment stability could be compromised by seepage and related processes that are facilitated by shorter seepage paths caused by pit formation. Pits might also change slope geometry enough to endanger slope stability. Conversely, slope stability might be increased by reduced vertical loading when trees are toppled by windthrow.

However, the probability of serious impacts from tree overturning is uncertain. Key issues include the probability of winds or water currents strong enough to uproot trees, the size of resultant pits, and the rapidity of scour and seepage processes relative to flood event durations.

Windthrow might affect trees anywhere on or near the levee, while overturning caused by water flow would be limited to the waterside of the levee, except instances of overtopping as simulated by Le et al. (2012) or when seepage compromises soil strength around the tree. For example, Shriro et al. (2012) reported results of a seepage experiment on an abandoned levee at Twitchell Island in the Delta. To examine effects of tree roots on seepage, trenches were excavated in the crest of a levee along the embankment centerline and filled with water. This loading caused seepage flows to emerge from burrows at the base of a leaning oak tree located at the waterside levee toe, eventually leading to its falling from an angle of 42° with the horizontal to 23° with the horizontal.

The available literature on treefall may be subdivided into four groups:

- studies that report the magnitude of forces necessary to uproot or break trees,
- approaches used by arborists and tree managers to assess the likelihood of damage from falling limbs or trees,
- analyses of the drag forces on trees caused by wind or water, and
- reports of the size of pits that result from tree windthrow.

7.2 Forces Required to Topple Trees

Windthrow is of interest to commercial foresters and forest ecologists. Accordingly, the literature on forces required to topple trees (reviewed by Peterson and Claassen [2013]) is dominated by results for smaller[8] trees (Nicoll et al. 2006) and studies of conifers in monoculture plantations (for example, Urata et al. 2012). Stathers et al. (1994) provide an overview of many variables that control windfirmness, particularly for conifers growing in stands on hillslopes (Table 7-1). Relatively little information is available on mixed stands of deciduous trees or trees grown at larger spacing than in plantations.

Work under the CLVRP (Peterson 2012, Peterson and Claassen 2013) represents the only documentation of forces required to uproot trees growing on levee slopes, and only the third report of winching tests on broadleaf trees (Peterson and Claassen 2012). Critical moments required for tree windthrow have been studied using scale models in laboratory wind tunnels, mathematical models, and static winching tests conducted on living trees in the field. Static winching field tests are conducted by applying a steadily increasing force to a standing tree by pulling with a cable attached by a winch to an anchor tree or a piece of heavy equipment (Figure 7-1a). The deflection angle of the trunk and applied force may be logged at frequent intervals until the tree trunk breaks or the tree is uprooted.

[8] For example, Nicoll et al. (2006) reviewed studies that reported tests of almost 2,000 trees from 12 conifer species that were mechanically overturned on 34 sites in the United Kingdom between 1960 and 2000. Species mean dbh varied from only 18.0 to 22.8 cm and species mean heights from 12.6 to 17.5 m.

Table 7-1. Factors Controlling Wind Firmness in Conifer Stands in British Columbia

Wind Force Factors		
High Hazard	**Moderate Hazard**	**Lower Hazard**
Topographically exposed locations: crest, saddles, upper slopes, etc.		Topographically protected locations
Boundaries on the windward edge of a stand	Boundaries parallel to the storm wind directions	Boundaries on the lee edge of a stand
Tall trees Large dense crowns	Trees of intermediate height Moderate dense crowns	Short trees Small open crowns
Resistance to Overturning		
Trees with low taper and no butt flare	Trees with moderate taper and moderate butt flare	Trees with high taper and large butt flare
Shallow rooting (less than 0.4 m)	Moderately deep rooting (0.4 to 0.8 m)	Deep rooting (greater than 0.8 m)
Root rot areas		No evidence of root rot
Shallow soils (less than 0.4 m)	Moderately deep soils (0.4 to 0.8 m)	Deep soils (greater than 0.8 m)
Poorly drained soils	Imperfectly to moderately well drained soils	Well-drained soils
Other Indicators		
Moderate to extensive natural windthrow present	Minor natural windthrow present	No natural windthrow
Extensive windthrow present on similar adjacent cutting boundaries	Minor to moderate windthrow present on similar adjacent cutting boundaries	No windthrow on similar adjacent cutting boundaries
Pit and mound micro-topography		No evidence of pit and mound microtopography

Source: Stathers et al. 1994
Notes: m = meter(s)
Filled cells indicate conditions observed on levee slopes in California's Central Valley.

Data output from static winching tests is typically converted to the critical moment for overturning about a point at the ground surface, M_{crit}, by summing the moment from the force applied by the cable, $M_{applied}$, and force from the weight of the leaning tree, M_{weight}:

$$M_{crit} = M_{applied} + M_{weight} = F_{applied} l \cos\theta + F_{applied}\delta_{xa} sin\theta + W_{tree}\delta_{xm} \qquad (4)$$

where $F_{applied}$ is the maximum force applied in the test, θ is the angle between the cable and the horizontal, l is the vertical distance from the ground to the point of cable attachment, W_{tree} is the weight of the aboveground portion of the tree, δ_{xa} is the horizontal displacement of the tree trunk at the point of cable attachment, and δ_{xm} is the horizontal displacement of the center of mass.

All quantities in this equation are measured simultaneously with the occurrence of the maximum applied force (red arrow in Figure 7-1b). Multiple inclinometers placed at intervals along the trunk are used to log tree deflection from the vertical and readings averaged to generate values for l, the displacements δ_x and θ.

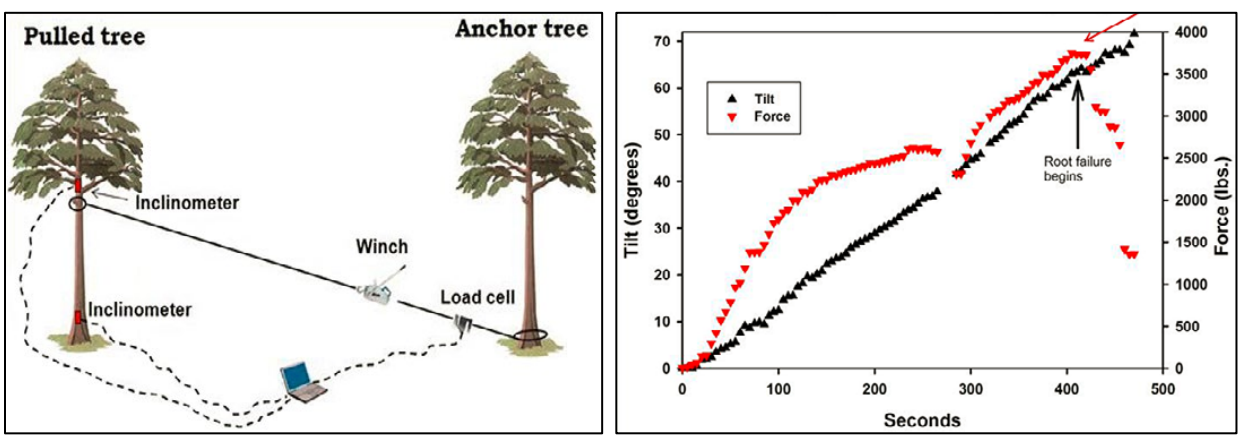
M_{crit} values are typically compared to the important controlling variables such as tree size, morphology, and species (e.g., Urata et al. 2012), and to site conditions including wind climate, slope, soil type and moisture, and proximity to neighboring trees (e.g., Lundstrom et al. 2007, Galinski 1989). Several authors have published regression formulas of the form

$$log\, M_{crit} = a + b\, log\, x \qquad (5)$$

or more simply,

$$M_{crit} = a + b\, x\,, \qquad (6)$$

where x is some measure of tree size such as dbh, mass, or trunk mass (see reviews in Peltola 2006 and Urata et al. 2012). Often these formulas are based on winching tests of relatively small conifers growing in forested stands, although Lundstrom et al. (2007) report results for 84 trees with dbh as large as 70 cm (min = 22 cm and mean = 46 cm).



Source: Peterson 2012

Note: During the test duration (x-axis is time), the tree tilts from an initial vertical position (black symbols, left vertical axis) to 70 degrees. Force (red symbols, right vertical axis) varies nonlinearly with tilt and time. Red arrow indicates maximum applied force used to compute M_{crit}.

Figure 7-1. (a) Schematic of Static Winching Test, (b) Output from Static Winching Test

Peterson (2012) and Peterson and Claassen (2012, 2013) describe methods for and results of static winching tests applied to two tree species common on California Central Valley levees: valley oak (*Quercus lobata*) and Fremont cottonwood (*Populus fremontii*). Trees at five study sites, all on Central Valley levees, were tested in winter during 2010 and 2011. Trees were typically pulled across the slope of the levee, but an examination of the data, including trees pulled upslope and downslope, revealed no systematic differences in critical moments based on

pulling direction. Tests reached one of three endpoints: trees were uprooted, stems broke, or trees reached the maximum deflection that the test apparatus could produce by bending their stems without breaking. The latter endpoint was limited to several small trees (dbh less than 20 cm); these were not included in statistical analyses and are not listed in Table 7-2. Peterson and Claassen (2012) also include supplemental results for three boxelder trees (*Acer negundo*) as well as six cottonwoods (*Populus* spp.) growing on nonengineered, natural floodplain soils.

Table 7-2. Summary of Results of Cable Winching Tests on California Levee Trees

	Cottonwoods	Valley Oaks	Total
Successful tests	21	45	66
Uprooting	11	24	35
Breaking	10	21	31

Source: Peterson and Claassen 2013

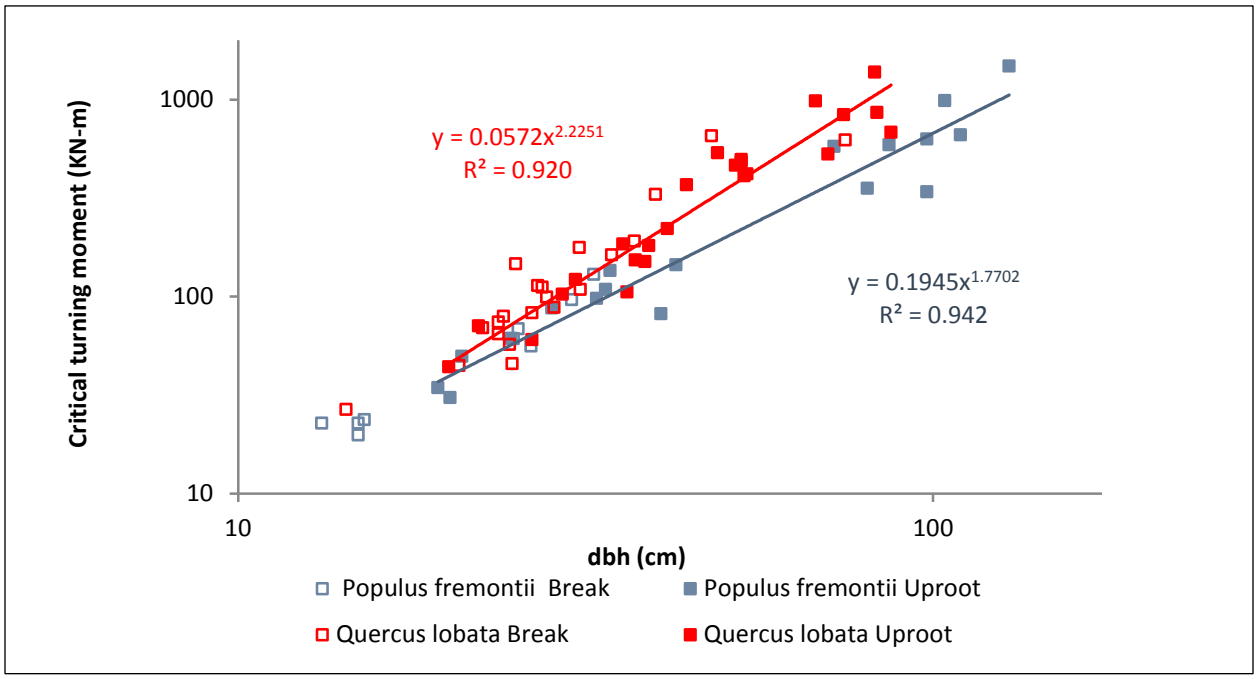
The tested levee trees tended to be isolated, and 37 had no neighboring trees within 5 m. Trees that broke instead of uprooting tended to be smaller and less isolated. Only five of the 35 trees that uprooted had neighbors within 5 m.

Soils were sampled at several depths and at various distances from the trunks; when trees uprooted, samples were also collected from pits. Soil bulk densities ranged from 1.26 to 1.98 g/cm^3. Soils were sandy (average sand content = 63%) and droughty, with moisture content = 24.8% $\pm$ 13.8% (mean $\pm$ standard deviation), despite the fact that tests were run during the rainy season. Presumably higher water contents would occur in levee soils under flood loading. However, literature on the effect of soil moisture on windthrow is equivocal (see discussion in Peterson and Claassen 2013).

In accord with results reported by others, large trees were more windfirm than small trees, with M_{crit} increasing with dbh in a nonlinear fashion (Figure 7-2). Aboveground tree mass was the strongest predictor (r^2 = 0.927, p less than 0.0001) of critical turning moment for valley oaks; and a surrogate measure of tree size (tree height times dbh^2) was the strongest predictor (r^2 = 0.947, p less than 0.0001) for cottonwoods.

Very large forces were required to uproot the largest trees, with critical turning moments generally ranging from 10^4 to 10^6 newton meters (Nm). When tree size is considered, results of this study are consistent with those reported by others, but near the high end of the range. For example, Urata et al. (2012) reported M_{crit} values on the order of 10^4 Nm for four stands of trees with dbh of 10–19 cm. Most trees tested by Peterson and Claassen (2013) were healthy. One tree with significant trunk rot had a low turning moment (approximately 3.4 x 10^5 Nm) considering its size (dbh = 98 cm).

Analyses of covariance indicated that differences in critical turning moment observed by Peterson and Claassen (2013) were not explained by soil characteristics or tree species. Species differed substantially in critical turning moment, but the high intersite variation led to the large interspecific differences being statistically insignificant. Conversely, differences between sites



Source: Data from Table 1 in Peterson and Claassen 2012

Curves are fit to uprooting data points only.

Figure 7-2. Turning Moment versus Diameter at Breast Height for Trees in Central California

and tree size were highly significant. Because tree and surface soil characteristics were similar among sites, Peterson and Claassen (2013) suggested that site differences may have been attributable to the deep subsoil environment: deeper rooting at some sites appeared restricted to vertical cracks while other sites had less-constrained rooting, consistent with reports by others (Fraser and Gardiner 1967 and Somerville 1979 in Peltola 2006). In general, winching tests of trees growing on levees exhibited trends similar to those reported for forest trees, which increases confidence in the levee tree results and allows limited inferences regarding levee trees to be drawn from the larger literature for forest trees.

7.3 Forces Required to Topple Infirm Trees

Research described in the previous section focused on healthy, living trees without obvious defects. Arborists and urban foresters have developed protocols for assessing the risk of falling trees or limbs damaging adjacent structures or vehicles or harming motorists or pedestrians (e.g., Ellison 2005). These protocols are based on visual assessments of the trees and nearby structures, frequency of traffic, and other site features. Several protocols include completion of standard forms (Koeser et al. 2013). Tree assessment is based largely on professional judgement, and "accurately assessing the probability that a tree or branch will fail is highly dependent on the skill and experience of the assessor" (Ellison 2005).

7.4 Drag Forces on Trees from Wind or Water Flow

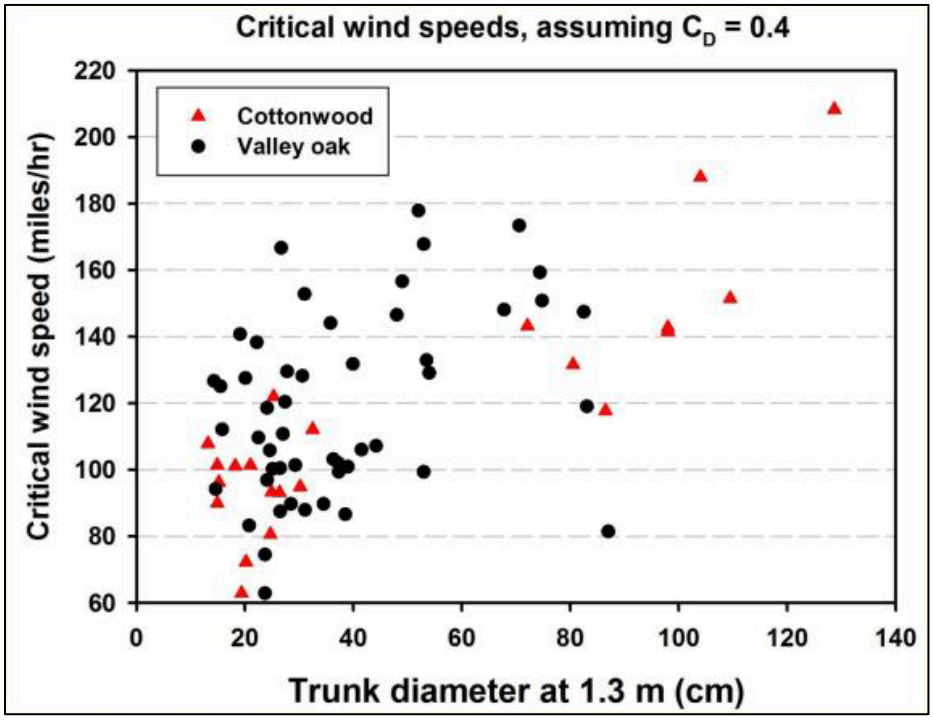
The magnitude of the drag force, F_d, exerted on a solid object by a flowing fluid with an approach velocity V is given by

$$F_d = \frac{\rho C_d A V^2}{2} \qquad (7)$$

where ρ is the density of the fluid, C_d is the drag coefficient, and A is the cross-sectional area of the object in the plane normal to the flow. Because trees bend and streamline themselves as velocity increases, both C_d and A may change as V increases, and likely reflect tree size, flexibility, and growth habit, suggesting that trees of a given size and species have similar drag coefficients. C_d values for broadleaf trees are lower when leaves are present because of the streamlined form that leafed trees assume in flow (Vogel 1989, Vollsinger et al. 2005, Wunder et al. 2011), but actual drag forces may be higher because of the larger projected cross-sectional area. Rundnicki et al. (2004) and Fathi-Moghadam (2007) suggest that C_d and Darcy friction factor, respectively, for conifers decrease exponentially with increasing wind speed. A similar relationship between wind speed and drag coefficient for broadleaved trees is suggested by Vogel (1989). However, Urata et al. (2012) used a constant value of $C_d = 0.35$ in their analyses, and Peterson used a constant value of $C_d = 0.40$ based on work by Kane et al. (2008).

If one assumes that the dynamic load imposed by wind may be represented by an equivalent static load (but note that the approach by Fathi-Mogadam [2007] accounts for resonant frequency of trees), and if a reliable approach for estimating C_d and A can be developed, Equations 4 and 7 may be solved for V, the wind speed required to produce M_{crit}. Several authors have presented models for computing critical wind speed from tree, stand, and site characteristics (Peltola 2006). Peterson and Claassen (2012) reported that the estimated critical wind velocities for the majority of trees they tested exceeded 40 m per second (m/s) (89.5 miles per hour [mph]), as shown in Figure 7-3. Only three trees, all less than 25 cm dbh, had critical wind velocities less than 30 m/s (67.1 mph), and all but two trees greater than 40 cm dbh had estimated critical wind velocities greater than 50 m/s (111.8 mph). Subsequent analysis of the Peterson and Claassen (2012, 2013) dataset revealed a small, systematic error that produced M_{crit} values about 4% lower than actual, which would lead to critical wind velocities 4% larger than those above (C. Peterson, personal communication, 2013).

Urata et al. (2012) reported critical wind speeds of 15–35 m/s (34–78 mph) for the small conifers they tested (dbh 10–19 cm). Risks of windthrow may be quantified by analyzing the frequency and duration of winds that equal or exceed the estimated critical speed. Winds of the magnitude estimated as critical occur rarely in the Central Valley of California, particularly for locations outside the Sierra Nevada and its foothills (Figure 7-4; see further analysis by Peterson and Claassen 2012). For locations in the Central Valley lower than the foothills, the probability of at least one 5-second wind gust greater than 22 m/s (50 mph) occurring on at least one day per year was computed to be less than 0.007.



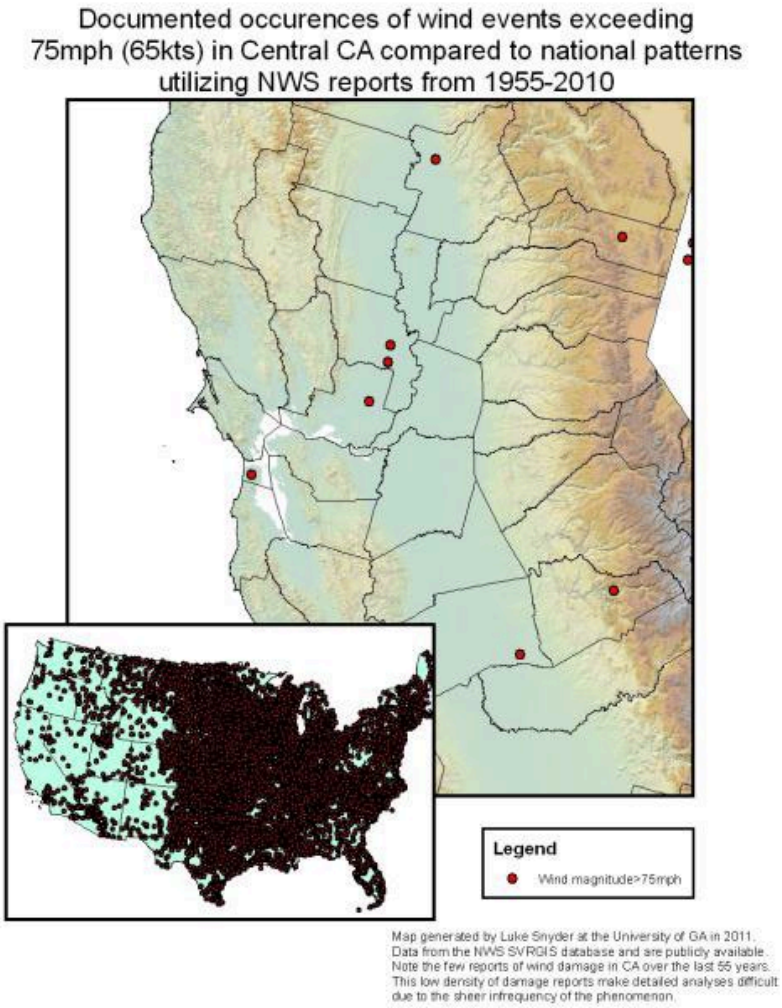
Source: Peterson 2012

Figure 7-3. Computed Critical Windspeed versus Trunk Diameter for Trees Winched by Peterson and Claasen (2012)

Water speeds required to overturn trees may be estimated using an approach similar to that for wind speed, but the density used in Equation 7 should be the density of water, and the area in Equation 7 should be the cross-sectional area of only the submerged portion of the tree projected in a plane perpendicular to the current direction. Assuming that 10% of the tree area is under water, the critical water-current velocities are about 11% of the critical air velocities, or 4.4 m/s (9.8 mph) for trees with critical wind speeds of 40 m/s (89.5 mph). This rough estimate ignores the nonuniform distribution of tree cross-sectional area and water velocity in the vertical direction, but more detailed computations would produce higher critical water velocities because tree trunks present their greatest area at the base where water velocities are lowest. On the other hand, water drag forces will be increased by trash and debris that collect around a standing tree, increasing its cross-sectional area, and additional forces on trees will occur if they are struck by floating debris with substantial momentum. These additional forces are difficult to reasonably estimate, but note the treatment of forces from impacts of floating debris by Knutson and Fealko (2014).

7.5 Root Pits and Mounds from Overturning

Rood et al. (2010) estimated root ball size in support of a vegetation variance request for the Natomas Levee Improvement Program. Based on literature and consultations with experts regarding tree root architecture, typical sizes for root balls of “large” levee trees were estimated



Source: Peterson 2012

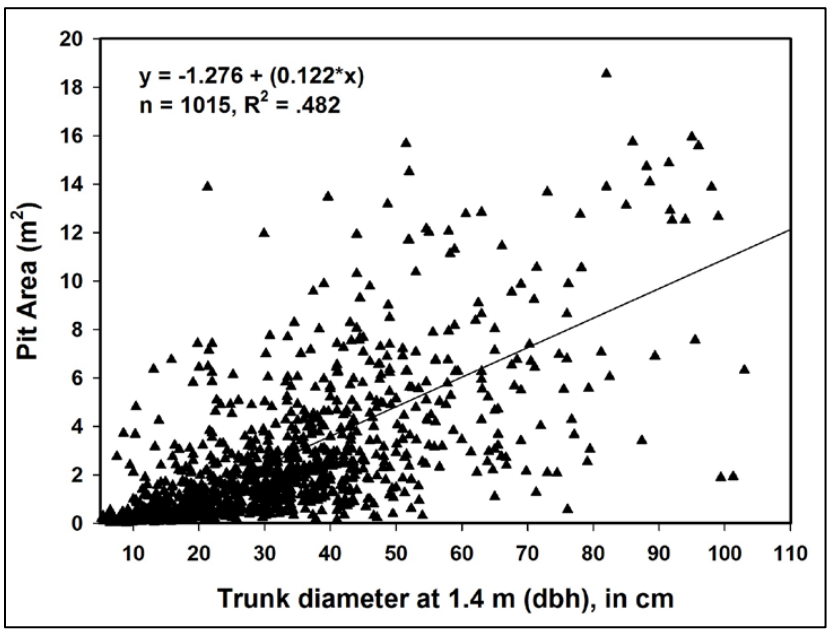
Figure 7-4. Weather Stations in Central California with At Least One Reported Instance of Windspeed Greater than 75 mph, 1955–2010

to be 3 ft thick and 15 ft in diameter. Maximum dimensions were estimated to be about 4 ft thick, and the root balls were estimated to extend about 20 ft in diameter laterally. Root ball dimensions of "small" trees were estimated to be 1 ft thick with a diameter of about 8 ft. These "thicknesses" correspond to root pit depths, while the root ball diameters may be converted to pit area using the formula for the area of a circle. A circular root ball 20 ft in diameter would emerge from a pit with an area of 314 square ft (30 m^2), considerably larger than the published measurements summarized below. Conservative assumptions may lead to larger pit sizes resulting from local scour or side-wall slumping.

Peterson and Claassen (2013) reported that pits generated from their winching tests had an average area of 4.11 $m^2 \pm 2.86$ m^2 and an average depth of 1.01 m $\pm$ 0.44 m, with a maximum

depth of 1.50 m. Root pit area was weakly correlated with trunk diameter but was not related to any other tree or site variable, including tree species and soil characteristics. Pit depth was also unrelated to tree and site variables, but did vary positively with tree mass (analysis of covariance, $p = 0.041$).

Sobhani et al. (2014) compiled data on root pits and associated mounds from 10 sites in six states. All sites were inventoried by the third author (Peterson) and his assistants, using consistent methods that allowed pooling data for statistical analyses. They found that for all 10 sites pooled, log-log regression using dbh as the independent variable explained almost 54% of the variation in the area of treefall pits (n=1,039) and treefall mounds (n=962). The resulting formula fit data from sites with numerous soil types, 31 tree species, and tree sizes ranging from 5 cm to greater than 105 cm diameter, albeit with wide scatter (Figure 7-5). Maximum root pit size was about 20 m^2.



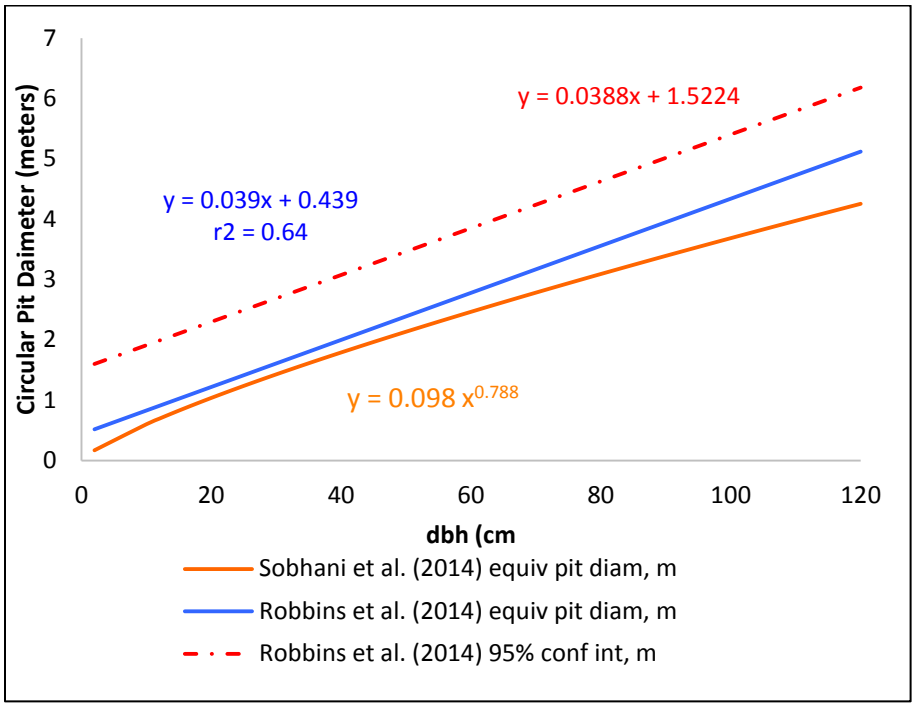
Source: Sobhani et al. 2014. Note that the data are fit slightly better by a power function ($y = 0.00755x^{1.575}$, $R^2 = 0.548$).

Figure 7-5. Log of Root Pit Area for Windthrown Trees from 10 Sites as a Function of the Log of Trunk Diameter

Robbins et al. (2014) conducted a thorough review of the literature relating treefall pit size to tree size. Because some studies reported pit area while others reported lateral dimensions (width and length or circular diameter), they converted all data to equivalent circular pit diameter, *D*, using the formula

$$D = 2\sqrt{\frac{Pit\ area}{\pi}}$$

They found 12 studies from a range of geographic locations with 676 data points usable to develop a relation between dbh and circular pit diameter, as shown in Figure 7-4. Several of these studies were also included in the aforementioned analysis by Sobhani et al. (2014). They suggested using the upper 95% confidence interval relation shown in Figure 7-4 to estimate treefall pit diameter. For comparison, the regression developed by Sobhani et al. (2014) and depicted in Figure 7-4 was converted to a relationship between dbh and equivalent circular diameter and plotted on the axis with the Robbins relation in Figure 7-6.



Sources: Sobhani et al. 2014, Robbins et al. 2014

Figure 7-6. Comparison of Regressions for Treefall Root Pit Diameter Against Diameter at Breast Height

The Robbins et al. (2014) equation produces pit diameter estimates that are 15% to 20% larger than those based on the one developed from the Sobhani et al. (2014) relation. Robbins et al. (2014) suggested that treefall pit volume may be conservatively estimated by assuming a cylindrical shape with this estimated diameter and a depth in m equal to 0.036 times the dbh in cm,[9] with an upper limit for depth of 2 m.

7.6 Data Gaps

Critical turning moments vary by species and site while drag coefficients vary by species, and existing datasets are limited to few species and few levee sites. Computations suggest that the

[9] Robbins et al. (2014) actually give this relation as depth (ft) = 0.3 dbh (in).

probability of treefall on California levees is small given the frequency of high winds and required forces, but these probabilities have not been assessed in light of actual treefall observations. Existing datasets are based on live, healthy trees. Protocols for assessing risk of tree failure or treefall exist (e.g., see Section 7.3 above) and are widely applied to infirm as well as healthy trees in urban settings, but no evidence was found that these methods have been validated.

7.7 Points of Scientific Debate

Error inherent in the assumption that the effects of wind loading, which involves gusts and other types of turbulence as well as tree swaying and vibration, may be represented by winching tests (static loading) is unquantified. The California levee dataset presented by Peterson and Claassen (2012, 2013), while both unique and exceedingly valuable, may overestimate the forces required for overturning trees in saturated soils.

As noted above, there are slight differences in published relationships between tree size (dbh) and pit size (diameter). There is some question as to how conservative an approach is needed in transferring regression results to design criteria: should pit volume be based on a conical or cylindrical geometry? Should the upper limit be the 90%, 95%, or 99% confidence interval?

7.8 Potential Implications for Levee Vegetation Management

A treefall event severe enough to endanger a levee represents the joint occurrence of several rare events: high winds, wind infirm trees, a flood event, and perhaps local scour. Small trees are most readily overturned but produce the smallest pits. The greatest hazard is associated with large, isolated, wind infirm trees growing near the top or at the landside toe of smaller levee embankments that fail by overturning rather than by breaking. Removal of significant material from the levee prism at these locations may increase the risk of overtopping, seepage hazard, or slope instability. An effort is under way in California to develop science-based procedures to identify and support the management (e.g., removal, trimming) of trees that pose an unacceptable threat to levee integrity. In the absence of better information, data cited in this chapter may be used as a guide to the wind forces needed to overturn a given tree and to estimate the size of the resulting root pit. Winds strong enough to topple healthy trees rarely occur in the Central Valley of California.

8 Impacts of Burrowing Animals on Levees

Abstract
Burrowing animals, especially California ground squirrels and Botta's pocket gophers, are ubiquitous in levees in the lower Sacramento River basin. Field studies have examined the associations between burrow presence on levee slopes and abundance and land cover at scales ranging from 5-m radii around burrow entrances to a scale encompassing lands lying within 75 m of the levee toe. In general, burrows were less frequent in areas with tree cover and leaf litter, but burrows became more frequent when landsides of grassed levees were adjacent to fruit or nut crops. Several forensic studies have implicated rodent burrows as causal or probable factors in levee failure. Recent research has included a literature review documenting the range of reported depths and lengths of ground squirrel burrows and field studies that included exhumation and mapping of burrows in two California levees. One burrow penetrated the levee embankment. Field and numerical experiments in two other studies indicated that burrows dominate seepage through levee embankments, even when large trees or stumps were present.

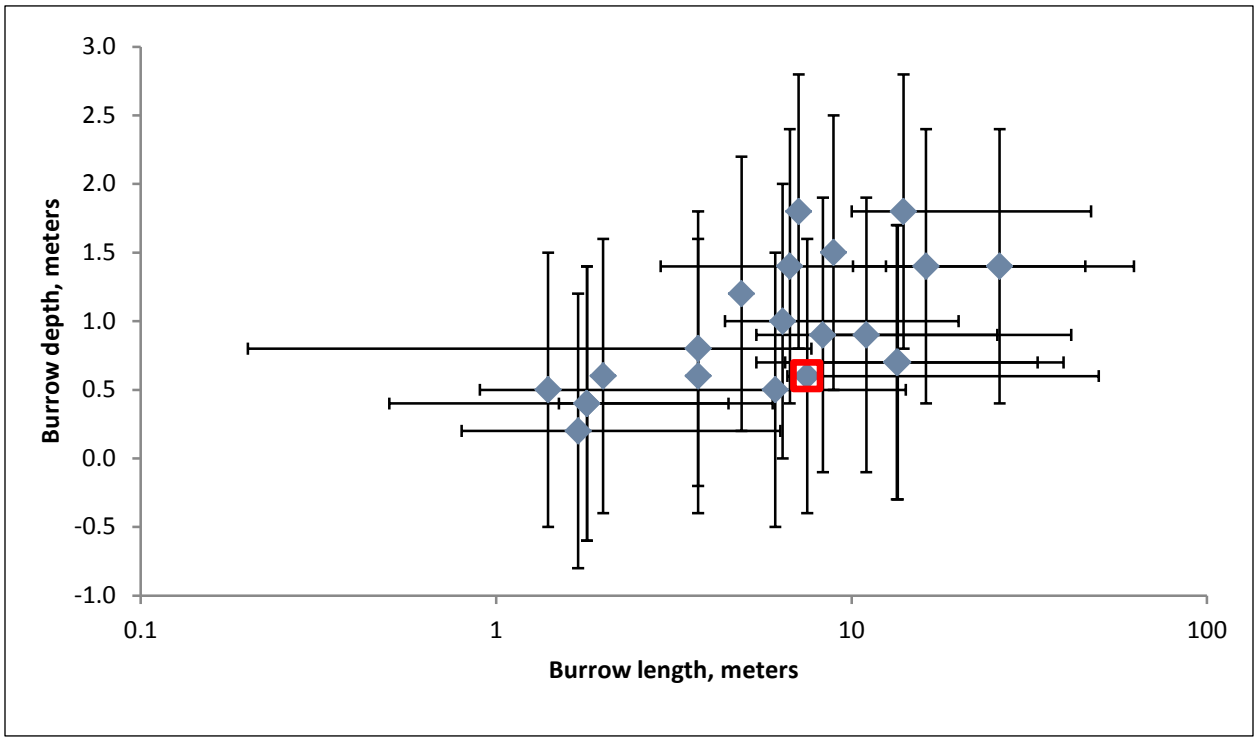
8.1 Animal Burrows and Levee Vegetation

Earthen levees typically provide habitat for a range of animal species, many of which burrow into the soil or use burrows created by other species (Bayoumi and Meguid 2011). These animals display preferences for certain types of habitat, which may include the presence or absence of woody vegetation; therefore, the presence or absence of woody vegetation on levees may affect the abundance of animal burrows. Furthermore, the efficiency of detection of burrows by visual inspection may be affected by vegetation. Animal burrows affect the reliability of levees in at least three ways (FEMA 2005 in Ordenaña et al. 2012):

- promotion of water seepage,
- creation of voids that can collapse and weaken or lower the levee, and
- soil disturbance at burrow entrance that can promote erosion that alters the levee profile.

Burrowing animals found on levees include worms, insects, mammals, and reptiles. Mammals are clearly the most significant in terms of hazard because of the size and extent of their burrows (e.g., see Figure 8-1). Species of concern include ground squirrels, gophers, and those that den in riverbanks such as beaver, muskrat, and nutria (Hynson et al. 1985, Bayoumi and Meguid 2011).

Animal burrows are ubiquitous in the levees of central California. Reports of the presence and extent of burrows have been prepared by Dixon (1922), Fitzgerald and Marsh (1986), Gray et al. (1991), Harder et al. (2012a), and Ordenaña et al. (2012). Key species in Central Valley levees include California ground squirrel (*Otospermophilus beecheyi*), which excavates burrows 9–13 cm in diameter and can reach aggregate lengths of 42 m (Ordenaña et al. 2012), and Botta's pocket gopher (*Thomomys bottae*), which has burrows that measure 4–6 cm in diameter (Van



Source: Van Vuren and Ordenaña 2012a

Error bars show maximum and minimum reported values. Red square indicates California ground squirrel, *Otospermophilus beecheyi*. Data compiled from the literature by Van Vuren and Ordenaña (2012a).

Figure 8-1. Mean Length and Depth below Ground Surface of Burrows of 22 Ground Squirrel Species

Vuren and Ordenaña 2011). Pocket gopher burrows are often backfilled with soil, but their burrowing may significantly alter the embankment profile, as they disturb major fractions of California grassland surface soils each year (see review by Ordenaña et al. 2012). Major efforts are expended in an effort to control squirrel populations on levees and fill their burrows (Hynson et al. 1985, Fitzgerald and Marsh 1986).

Recent research by Ordenaña et al. (2012) included examining both sides of 166 segments, each 50 m long, of 12 levees located within 80 kilometers (km) of Sacramento, California. Totals of 5,705 California ground squirrel burrows and 33,678 burrows attributed to Botta's pocket gophers were found, for an average density of 0.69 squirrel burrow per m and 4.06 gopher burrows per m of levee. Squirrel burrows were found in 98% of the segments examined and gopher burrows in 95% of the segments. Earlier work by Daar et al. (1984) reported 0.06 to 1.19 ground squirrel burrows per m along 3.2 km of levee along the East Yolo Bypass, Yolo County, California. Landside densities averaged three times greater than waterside densities. Burrows were counted in late summer 1980 after levee vegetation had been burned.

8.1.1 Habitat Associations

Burrowing mammals have been shown to prefer certain habitat types; therefore, levee vegetation management may positively or negatively affect the hazard posed by burrows. Kleber-

Lerchbaumer (2012) noted that several mammal species burrow in earthen levees in Germany, but problems are caused almost entirely by beavers, which are attracted by woody vegetation. Cobos-Roa et al. (2012a) also presented a few photographs of severe damage to California levees by beavers.

A few studies have examined the associations between selected burrowing mammals and habitat characteristics on levee slopes, including vegetation. Fitzgerald and Marsh (1986) reported results of a 15-year effort by DWR to control ground squirrels by planting selected shrubs, ground cover, and grasses, notably the tall bunch grass *Pharis tuberosa* (Perla grass). The selected plant species either failed to thrive or failed to reduce squirrel populations. Some indications suggested that squirrel habitat benefited from the plantings. More extensive study of habitat associations was part of the aforementioned study by Ordenaña et al. (2012), who examined the relationships between burrow density and vegetation at both the microhabitat and macrohabitat scales. The same team later analyzed effects of land cover at the landscape scale on squirrel burrows in levees (McGrann et al. 2014).

Microhabitat

Ordenaña et al. (2012) examined burrows found on both sides of 166 segments, each 50 m long, of 12 levees located within 80 km of Sacramento, California. Microhabitat associations were examined by estimating the habitat immediately surrounding (within 5 m of) burrow entrances in 131 of the 166 levee segments that supported at least two macrohabitat types. Only burrows located in the middle of the levee slope were assessed, so that all of the 5-m radius circle centered on the burrow would lie on the levee slope.

In addition, analysis was conducted for cover at the canopy level and at the ground level. First, microhabitat was classified at the canopy level as either “open” or “tree cover.” Next, microhabitat at the ground level was assessed with percentages assigned to tree boles, leaf litter, shrubs, grassland, barren, riprap, gravel, and pavement. Habitat preferences were quantified by computing the ratio of percent cover of a particular type within the 5-m radius circles to the percent cover of the same type for the entire levee segment. Thus, a burrow inside a clump of shrubs (such as 80% shrub cover within the 5-m radius) on a levee with only 20% shrub cover for the 50-m segment would have a habitat preference ratio of 80/20 = 4.0. Ratios greater than 1.5 were assumed to indicate preference, while ratios less than 0.67 were assumed to indicate avoidance. Both ground squirrels and pocket gophers showed a preference for barren areas and an avoidance of trees, leaf litter, riprap, gravel, and pavement. Pocket gophers avoided leaf litter, tree boles, and gravel.

Macrohabitat

Ordenaña et al. (2012) examined burrows found on both sides of 166 segments, each 50 m long, of 12 levees located within 80 km of Sacramento, California. Macrohabitat analyses compared the number of burrow entrances in each levee segment with the percent cover of various vegetative types. Cover by tree canopy was included as a separate item. Statistical analyses included logistic regression (with burrow presence or absence as the dependent variable) and Spearman’s rank correlation analyses (McDonald 2014). Separate analyses were performed for

waterside and landside slopes; all levees had paved roads on their crowns, and these were not considered in the cover assessment.

Logistical regression showed negative relationships between tree cover and ground squirrel burrow presence and leaf litter and ground squirrel burrow presence; no results were obtained for pocket gophers because they were present in almost all segments. Correlation analysis (Table 8-1) showed negative associations between burrow numbers for both species and tree cover and leaf litter. Squirrel burrow numbers were positively related to shrub cover on the waterside and grassland on the landside. Gopher burrow numbers were positively related to grassland cover.

Table 8-1. Results of Spearman's Rank Correlation Analysis of Associations between Macrohabitat Types and the Number of Burrows of California Ground Squirrels and Botta's Pocket Gophers for 166 50-Meter-Long Levee Segments in the Sacramento Valley, California

Species	Habitat	Land	Water
California ground squirrel	Tree cover	–	0
	Leaf litter	–	–
	Shrub	0	+
	Grassland	0	0
	Barren	0	0
Botta's pocket gopher	Tree cover	–	–
	Leaf litter	–	–
	Shrub	0	–
	Grassland	+	+
	Barren	0	0

Source: Ordenaña et al. (2012)

Notes: Each levee segment analyzed was 50 meters long. A plus sign (+) indicates *r* is greater than 0 and *p* is less than 0.05, a minus (-) indicates *r* is less than 0 and *p* is less than 0.05, and a 0 indicates *p* is greater than 0.05.[10]

Landscape

Daar et al. (1984) reported that ground squirrel burrows were higher on Yolo Bypass levee slopes where vegetation had been suppressed by overgrazing, and even higher on slopes within

[10] The letter *r* stands for the correlation coefficient, which is a measure of the strength of the linear association between two variables. If *r* is greater than 0, then the variables tend to increase and decrease together; if *r* is less than 0, one variable increases when the other decreases, and vice versa. Because this table presents results of rank correlation, it shows the association between the rank of the number of burrows (all sites were ranked based on burrow number) and habitat type (the % cover for each site was visually estimated, and then sites were ranked based on % tree cover, ranked again based on % leaf litter, etc.). The letter *p* stands for the probability that the value of *r* that was found could occur due to chance alone. A + sign in the table indicates that there was a positive association between the rank of the burrow abundance (e.g., shrub cover on the water side and California ground squirrel burrows) and that the *r*-value was large enough that there is less than a 5% chance that this association is due to chance (random variation in the sampled variables).

foraging range of a walnut orchard. The sample size was too small, however, to allow statistical testing. McGrann et al. (2014) examined landscape associations of California ground squirrels with burrows in levees in the Sacramento River valley, California. Well-separated, randomly selected 50-m segments of grassed landside levee slopes were examined for burrows, and land use within 75 m of the levee toe was visually classified. A total of 248 levee segments were surveyed, and squirrel burrows were found in 23% of segments. Only 6% of segments adjacent to grasslands had burrows, while burrows were found in 34% and 27% of levees with adjacent nut crops or perennial fruit crops. The relationship of the abundance of burrows to the adjacent vegetative cover was examined using bivariate logistic regression, and significant positive correlations between burrow abundance and the percent cover of perennial nut and fruit crops were noted. A significant negative relationship was noted between burrow abundance and the percent cover of grasslands.

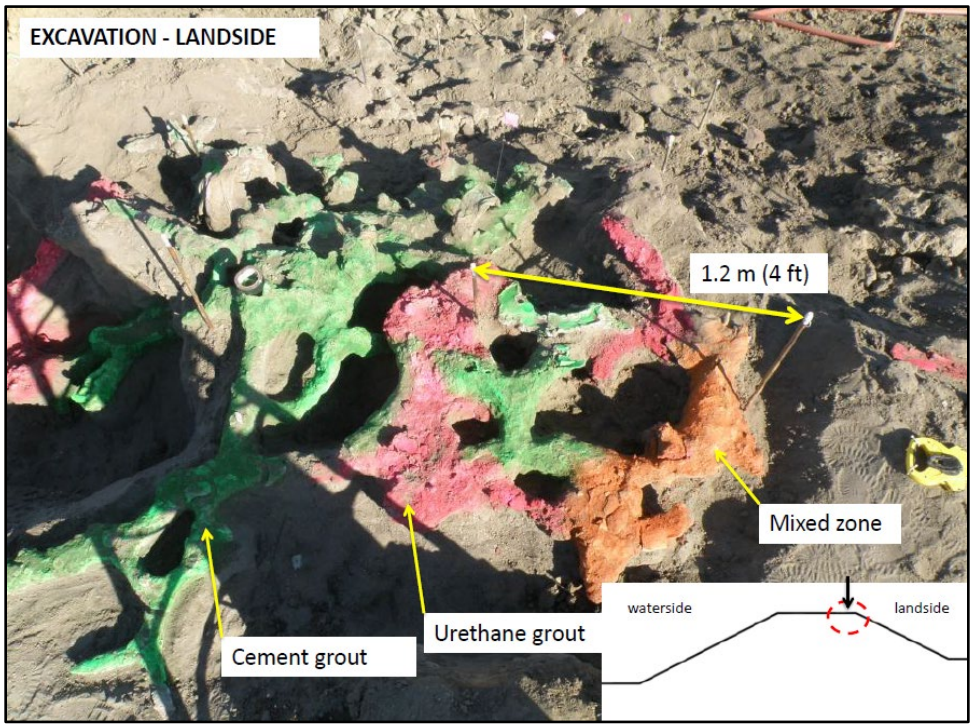
8.2 Potential Impacts on Levee Function

Because of the links between habitat type and abundance of burrowing mammals, some have argued that that influences on the amount of mammal burrowing may be the most important influences of levee vegetation management on levee function rather than direct effects on slope stability, root-induced seepage and piping, windthrow, local scour, etc. Animal burrows have been cited as causal factors or probable factors in numerous levee failures (Dixon 1922, Fitzgerald and Thompson 1988, Paul and Slaven 2009, Harder et al. 2009, U.S. Bureau of Reclamation 2008, Bayoumi and Meguid 2011, Harder 2012c).

Recent research has documented the extent and architecture of ground squirrel burrows and efficiency of grouting as a control measure. Extensive ground squirrel burrow systems in 20-m-long segments of two central California levees were grouted, and then the castings were excavated by Cobos-Roa et al. (2012b): Site 1 was a sandy levee that had no previous burrow grouting and Site 2 had been regularly grouted since 1998 and was comprised of clayey soils.

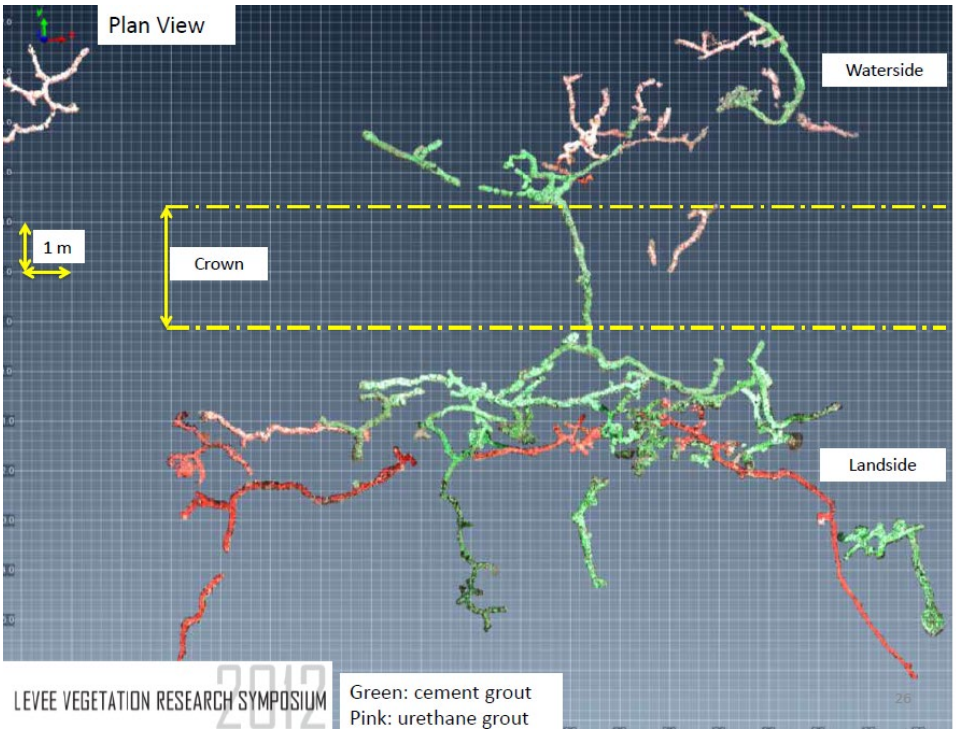
Site 1. Two methods were used to fill burrows with grout. First, individual burrows were identified and filled with cement grout using the standard approach employed by DWR to mitigate animal burrows. Secondly, a grid of metal tubes was implanted in the levee and a polyurethane grout was injected to fill voids that were not filled by the cement grout. Then the resulting castings were exposed by removing the surrounding soil (Figure 8-2). Only 76% of the burrow volume was filled with the standard procedure using cement-bentonite grout, leaving 24% that was filled using the urethane. The length, depth, and complexity of the burrows were impressive.

Site 2. The clayey levee was also devoid of vegetation. This levee had been actively grouted since 1998. An almond orchard was located adjacent to the landside. About 110 inactive or collapsed burrows and 12 active burrows were found, and one burrow completely penetrated the levee embankment (Figure 8-3), confirming the conclusion of Van Vuren and Ordenaña (2012b) that “California ground squirrels have the potential to burrow entirely through a levee.” About



Source: Cobos-Roa et al. 2012a

Figure 8-2. Excavation of Burrows at Site 1

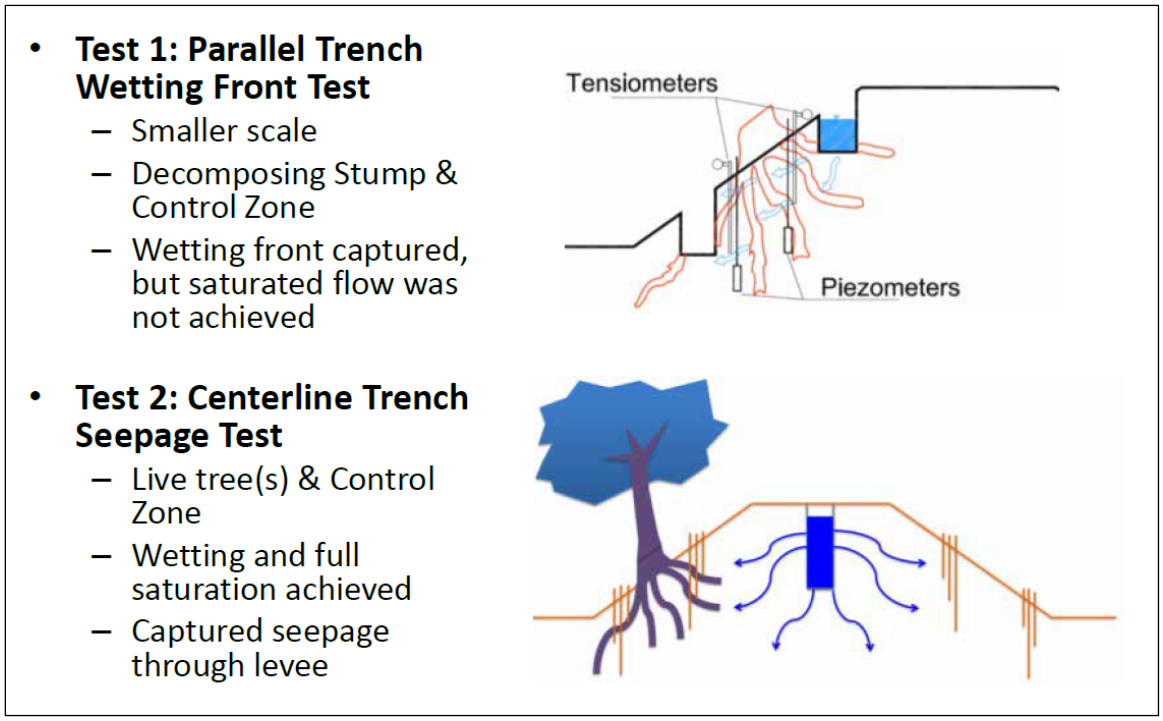


Source: Cobos-Roa et al. 2012a

Figure 8-3. Plan View of Burrows Exposed by Excavation of Clayey Levee

82% of the total site burrow volume was filled with the standard procedure using cement-bentonite grout, leaving 18% that was filled using the urethane.

Additional research at two other California sites showed that burrows dominated water movement through levee embankments. Shriro et al. (2012) reported the results of two field experiments where trenches were excavated high on central California levee slopes or along the centerline, parallel to the centerline, and were filled with water to observe the effects of tree roots on seepage flows. Seepage emergence in a downslope trench parallel to the water-filled trench was observed, and a network of tensiometers was deployed across the intervening slope (Figure 8-4). In Test 1, a dead stump was located between the parallel trenches. There was no preferential flow through live or decaying roots, but a mammal burrow dominated flow, accounting for the first emergence of water downslope (within about 30 minutes of initial loading) and the greatest volume of flow through the duration of the experiment. The wetting front progression was actually retarded by the stump relative to a control section without any trees or stumps between trenches.



Source: Shriro et al. 2012

Figure 8-4. Schematics of Field Experiments of Influence of Tree Roots on Seepage

In Test 2, a large, leaning oak tree near the waterside toe fell over during the test. As in Test 1, burrowing mammal holes played a significant role in determining flow patterns and early seep locations. Water was observed emerging from burrows near the tree. Larger burrows were attributed to muskrats, while smaller ones may have been from voles or gophers. Levee soil stratigraphy was important in determining seepage patterns, and at the time of the 2012 report, investigators had not been able to disaggregate the effect of the tree from stratigraphic effects.

8.3 Modeling

Cobos-Roa et al. (2012b) created 2D numerical models of water seepage through soil matrices with gaps or voids that partially penetrated the soil matrix. These gaps represented animal burrows in a levee that did not fully penetrate the embankment. The models were validated using actual field data from controlled seepage experiments in California levees. Model output showed the progress of wetting front and water flow with time after application of a constant head on one side of the soil matrix (simulated levee). Open gaps such as animal holes affected the wetting patterns within an unsaturated levee, and burrow impacts were much stronger than those associated with the subsurface structure of dead or living vegetation.

Seepage behavior was strongly affected by soil permeability. For a coarse-grained soil, the flow through discontinuous open gaps was negligible compared to the amount and velocity of flow through the high-hydraulic-conductivity soils. For a fine-grained soil, flow in discontinuous open gaps was limited by delivery of water from the relatively impermeable surrounding soil matrix. In both cases, computed flows (and piping potential) through the isolated discontinuities were low and highly dependent on the rate of flow through the soil matrix. Greater danger is associated with continuous penetrations. For continuous holes that penetrate the levee, piping potential is a function of hydraulic head (river level relative to depth of hole) and material properties. Burrows with waterside entrances also pose a hazard as they shorten the time to local saturation.

8.4 Data Gaps

No longitudinal studies have been conducted on levees converted from tree cover to grass cover (or vice versa) to directly observe the impacts on abundance of burrowing animals. It remains unclear whether the presence or absence of trees on levees has much impact on burrowing-mammal abundance when those levees are adjacent to fields under cultivation for fruit or nut crops. Most data regarding interactions among burrowing animals, vegetation, and levees are from the Sacramento River basin. Wider geographic coverage is needed for California and other geographic areas.

Because agricultural production will continue to provide animal food sources near levees, burrows must be managed using levee habitat modification, lethal controls, or burrow grouting. It is unknown how long-term grouting programs will affect the reliability (e.g., seepage properties) of earthen embankments. Furthermore, it appears that 20% to 25% of burrow voids are missed by standard grouting procedures. Structural controls such as those used in Germany may provide a positive barrier to all biological penetrations—both plant and animal.

8.5 Points of Scientific Debate

Controversy attends exact habitat associations among animal populations and vegetation. California research indicates that "…conversion of woodland habitats to grasslands on levees in

the Sacramento Valley will probably increase habitat quality for both ground squirrels and gophers, and thereby increase the potential threat that their burrowing activities pose to levee integrity." However, anecdotal reports from Germany suggest a positive association between beaver and woody plants on levees. Finally, the relative importance of vegetation on the levee slope and in areas adjacent to the levee (landscape) is not fully understood, so it remains unclear how effective it would be to allow woody cover on levees adjacent to fields under cultivation for fruit or nut crops.

8.6 Potential Implications for Levee Vegetation Management

Burrowing animals pose a known serious risk to earthen levee embankments. Seepage experiments and forensic investigations of failed levees suggest that animal burrows are much more dangerous to levee embankments than tree roots. The greatest danger is associated with networks of burrows or voids that create a continuous penetration through the embankment. Burrows with waterside entrances also pose a hazard as they shorten the time to local saturation. Responses of burrowing mammals to vegetation management may vary from one ecoregion to another, but according to one extensive study, California ground squirrels display a positive association with habitats on levee slopes free from woody species and avoid habitats with woody species or leaf litter. "The conversion of woodland habitats to grasslands on levees most likely will result in increased occurrence, abundance, or both of ground squirrels and pocket gophers, and thereby increase the potential threat that their burrowing activities pose to levee integrity" (Ordenaña et al. 2012). Ground squirrel burrow abundance also displays association with vegetation at the landscape scale, with burrows less common in levee slopes bordered by grasslands and more common in burrows bordered by fruit and nut crops. Traditional practices for combating burrows include filling of burrows with grout, use of baits and poisons, and fumigation. Some reports indicate that subterranean barriers may provide protection against levee embankment penetrations by burrows (Kleber-Lerchbaumer 2012, Witmer et al. 2012).

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9 Effects of Trees on Seepage and Piping in Levees

Abstract

During flood events, concentrated seepage may trigger progressive piping that compromises levee integrity. Living or dead roots from trees growing on or immediately adjacent to levees potentially create preferential seepage paths or voids. Even if piping does not occur, observed and simulated changes to seepage patterns associated with levee vegetation can modify soil moisture within the levee embankment, degrading or improving slope stability.

This chapter reviews three field experiments examining the effects of trees on water movement through levee embankments. The first experiment examined downslope water movement from a longitudinal trench excavated near the levee crown for a levee segment containing no woody vegetation and one containing a dead, decaying stump. Water flowed more slowly through the region containing the stump than through the region with no woody vegetation, and water movement was dominated by flow through animal burrows in both segments tested. The second experiment examined downslope water movement from a trench excavated along the levee crest. Trees occurred on both waterside and landside slopes. Water movement was governed by animal burrows and soil stratigraphy. No instances of preferential flow along roots were noted. The third experiment examined flow from an experimental basin surrounded by levees constructed with shrubby willows incorporated into some segments of the embankment. Hydraulic loading of embankments with willows and those with only herbaceous species produced almost identical responses.

Also reviewed in this chapter are several studies that used two-dimensional (2D) numerical models to examine effects of woody vegetation on seepage. Because clear-cut information about the effect of vegetation on levee soil hydraulic conductivity was not available, the models represented subsurface vegetation (roots) as regions of the levee embankment that had either depressed or elevated hydraulic conductivity relative to surrounding soils. The first study, based on a simple model, noted that decreasing the hydraulic conductivity by a factor of 10 for a 0.3-m-thick surface layer over the entire cross section of a sandy levee elevated the phreatic surface on the landside slope and increased the seepage discharge area on the slope. Another study obtained similar results using similar variations in conductivity but a more sophisticated model that involved coupling of transient seepage and deformation. Another group of 2D studies involved representing the root zone of a tree as a rectangular block placed at various locations on or adjacent to the levee. The root zone block was assumed to have either greatly depressed or elevated hydraulic conductivity relative to surrounding soil, or was subdivided into many much smaller cells that were randomly assigned widely varying conductivities. The simulated root zones generally affected only the flow field within their immediate vicinity, and this tendency was reinforced by a limited number of 3D model studies with similar approaches for representing vegetation. A root zone with a hydraulic conductivity 100 times smaller than the surrounding soil that was placed on or just beyond the landside toe and at the bottom of a dewatered drainage ditch increased the exit gradient by about 50%. Random assignment of hydraulic conductivity to small subdivisions of the “root zone” produced much larger seepage velocities than the “no root” condition when the random assignments resulted in contiguous zones of high conductivity that created preferential flow paths.

Another group of 2D studies examined the effects of a root that created a small-diameter vertical defect running from the landside floodplain soil surface through the soil blanket into an underlying permeable layer. Seepage gradients were definitely increased by the presence of the vertical defect over cases with no defects. Seepage analyses based on this “vertical defect” were developed for four levee projects in the western U.S. and the hazard of piping erosion was evaluated using an approach by Schaefer et al. (2010). One of the four sites appeared to be at risk for piping. A final group of 2D simulations modeled seepage through hypothetical, idealized blocks of uniform soils with various numbers of horizontal tubular voids of various sizes. Although the presence of the voids destabilized the wetting patterns within the soil block, overall effects of the discontinuous voids were slight because the permeability of the surrounding soil controlled flow into and between the voids.

Three-dimensional (3D) simulations of the effects of trees on levee seepage included idealized studies of hypothetical levees that simulated root zones as either finely gridded prisms with modified, heterogeneous hydraulic conductivity or higher fidelity depictions of a single tree root mass derived from Light Detection and Ranging (i.e., LiDAR) imagery of the exhumed root mass of a real tree. In general, the effect of a single tree on the levee performance was less in the 3D simulation than for similar 2D simulations. Another 3D investigation was aimed at reproducing the seepage patterns observed in the first field experiment described above. As in the field experiment, seepage was dominated by water movement through a mammal burrow.

9.1 Relevance to Levee Performance

Root-induced seepage is one of the most frequently cited potential hazards associated with trees on levees. It has been suggested that seepage can occur as water moves along small voids between the outer surfaces of roots and the soil or through larger voids created by decaying roots. The seriousness of such seepage is controversial, however. Plant cover generally increases the permeability of surface soils, but in some situations (e.g., where dense ground cover traps windblown fines), plant cover could conceivably cause a reduction in permeability. Attempts to relate hydraulic conductivity to vegetation cover on levees have failed to demonstrate a consistent pattern (Corcoran et al. 2011, Khalilzad et al. 2013). In fact, fieldwork reported by Corcoran et al. (2011) indicated that the hydraulic conductivity of levee soils adjacent to trees was not statistically significantly different from that of soils distant from trees. As noted above, Shriro et al. (2012) reported that seepage through levee soils containing a decaying stump was slow relative to seepage through soils under only herbaceous cover, but patterns of water movement were dominated by animal burrows.

Forensic evidence for the presence or absence of root-induced seepage is typically destroyed when levee embankments fail. In general, the impacts of woody vegetation on seepage and piping through a levee embankment are poorly understood relative to the effects of vegetation on slope stability. However, slope stability computations require information about soil moisture and groundwater levels within the embankment because of the major influence that these quantities have on soil strength and structural stability.

Experiments and observation indicate that flow through earthen barriers such as landfill or pond liners, cutoff walls, dams, and levees can occur through soil micropores and larger macropores. Bulk hydraulic conductivity for soils with macropores can exceed the bulk hydraulic conductivity for soil without macropores by several orders of magnitude even if both soils have the same void ratio (Gray 2013). The relative importance of macropores versus micropores in controlling bulk hydraulic conductivity of silty clays has been studied by running permeability tests on silty clay soil specimens compacted at different molding water contents. If one specimen is compacted dry of optimum water content and the other wet, the soil compacted dry of optimum will have a different internal pore structure with more macropores than the wetter soil. The macropores tend to dominate the flow regime, even for two soils at the same void ratio or dry density. In fact, it is possible for the hydraulic conductivity of the soil with the macropores to

exceed the hydraulic conductivity of soil with the micropores by several orders of magnitude even though both soils have the same amount of interstitial space through which water can move (Gray 2013).

Macropores occur as a result of a variety of processes in addition to root growth and death (ILIT 2006). These processes are related to features such as:

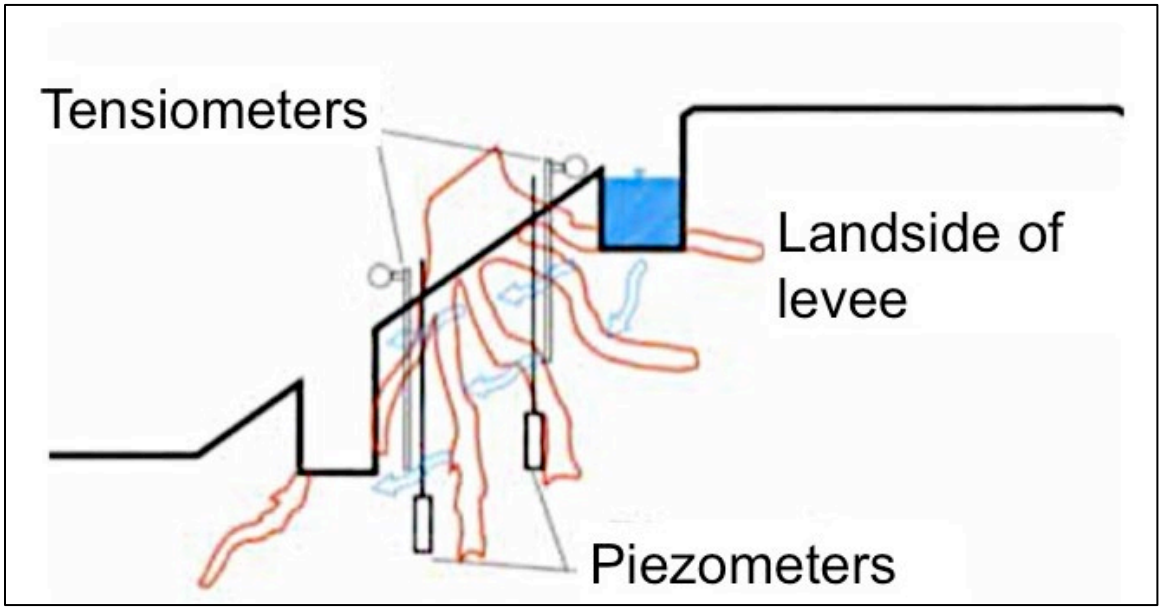
- shrinkage cracks;
- hydraulic fractures, which can occur in the absence of preexisting cracks, fractures, or macropores (Sherard 1986);
- contact surfaces (e.g., compaction lift planes);
- rodent burrows; and
- soil pipes (from washout of fines through gap-graded soils).

Macropores or "void volume defects" of one type can communicate with other types to create preferential flow paths (Gray 2013). Furthermore, voids do not have to be continuous to facilitate and accelerate water movement through the soil structure (Nieber and Sidle 2010). However, a simple model of flow through void volume defects in landfill liners has shown that the flow rate for a given hydraulic gradient is related to the depth of the defect relative to liner thickness, with a rapid increase in flow rate when the depth of the defect exceeds 0.8 of the liner thickness (Gray 1984, 2013). Landfill liner thicknesses tend to be much smaller than the thickness of levee embankments or landside soil blankets, with typical values for clay landfill liner thicknesses ranging from 2 to 5 ft. As stated in Chapter 2 of this report, tree roots are typically limited to the top 1 m (3.3 ft) of soil, but exceptions occur, particularly cottonwood roots.

Some workers have noted that seepage may be facilitated by removal of soil from a landside pit when a large tree is overturned by windthrow, thus shortening the seepage path (Duncan 1999). The effect of treefall (tree uprooting by wind or water flow) on levee stability is addressed in Chapter 7, "Hazards to Levees from Treefall."

9.2 Field Experiments

A field experiment reported by Shriro et al. (2011, 2012, 2014a) ("wetting test 1") included excavation of trenches on the landside levee slope of a silty levee in the Sacramento area, running parallel to the levee centerline and flanking a dead, decaying eucalyptus stump (Figure 9-1). The stump remained from a tree that was likely planted in 1964 and cut in 1993, or about 17 years before the study. Partially decayed roots, holes associated with ants and earthworms, and mammal burrows were frequently encountered when excavating the trenches (Shriro 2014a). The upper trench was filled with gravel and then loaded with water to conduct a "wetting test" (Figure 9-1). Similar testing was conducted on the same levee slope a short



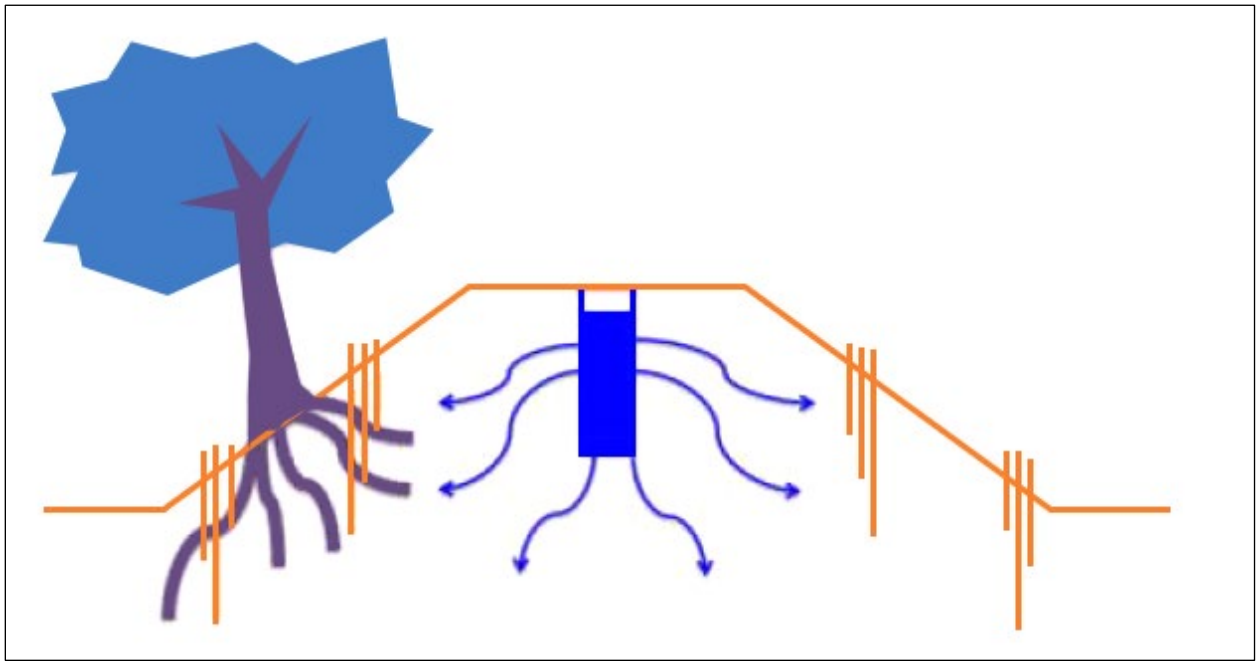
Sources: Shriro et al. 2011, 2012

Figure 9-1. Simplified Schematic of Wetting Test 1

distance away, where the slope was free from trees and stumps ("control area"). Movement of water downslope was monitored using a network of tensiometers and piezometers. Tensiometers were sealed using silica flour. The permeability of the levee and underlying floodplain soils allowed water to move vertically downward from the upper trench so that about half of the water that was applied to the upper trench was transmitted away from the slope and the lower trench, and fully saturated flow was not achieved throughout the levee cross section between the upslope and downslope trenches, although there were zones of saturation.

Visual observations of silica flour movement along decomposing roots for distances ranging from a few inches to 5 ft were reported. Silica flour migration seemed to be limited to cases where the tensiometers had been inserted so that they intercepted void spaces in decaying roots. No water movement was noted along live roots or along decaying roots that were not intersected by piezometer excavations. During the wetting test, water movement in both the stump area and the control area was dominated by flow through a network of shallow mammal burrows, highlighting the importance of macropore flow. Flow through the region containing the stump was slower than for the adjacent control area, which was under only herbaceous cover. The area directly downslope from the stump was the last to saturate during the wetting test.

Shriro et al. (2012, 2014b) also described a second wetting test experiment in which a trench was excavated along the centerline of an earthen levee that had a large tree growing at the waterside toe and another on the landside slope. As before, trenches were excavated along the levee segment containing the trees and along a nearby control area that supported only herbaceous cover (Figure 9-2). In this case, the levee comprised silty soils (identified as "ML") overlying less permeable silty materials (identified as "MH"), and saturated flow occurred.



Source: Shriro et al. 2012

Figure 9-2. Simplified Schematic of Field Test 2

Full saturation of levee soils were achieved, and as in the first test, burrowing mammal holes played a significant role in determining flow patterns and early seep locations. Seepage emerged next to the waterside tree in association with muskrat burrows. In this test, Shriro et al. (2012) reported that the levee and floodplain soil stratigraphy were evidently important in determining seepage patterns, and may have confounded the effects of tree roots on seepage. No decomposing roots were noted, and no instances of preferential flow associated with live roots were noted (Shriro et al. 2012).

Lammeranner et al. (2009b) and Lammeranner (2012) describe measurements of seepage through an experimental, prototype levee embankment constructed by the research team. One section had shrubby willows incorporated into the embankment surface in four standard bioengineering configurations and an adjacent section of the embankment was planted with sod for comparison purposes. Willows developed shallow but dense growths of fine roots despite soil dry densities between 1.886 and 2.028 g/cm^3 (Lammeranner et al. 2008). Seepage was monitored using piezometers, soil moisture sensors, and soil temperature probes, which were built into the embankment during construction. Steady-state, long-term hydraulic loading of embankments vegetated with willows and herbaceous species produced almost identical soil moisture and piezometric responses.

9.3 Two-Dimensional Numerical Simulations

With the difficulty of obtaining forensic and experimental data, root-induced seepage and piping have been studied using numerical models. Flow through macropores can dominate water movement through natural soils (Beven and Germann 2013), and the intensity of macropore flow varies with the type of vegetative cover (grass or trees; Bachmair et al. 2012). However, modeling efforts typically assume that entire embankments, specific layers, or specific cells are modified by roots to have more or less uniform properties because of the complexity of preferential flow (e.g., Shields and Gray 1992, Fox et al. 2009). 2D models ignore variations in the longitudinal direction and represent the levee embankment with a typical cross section. Therefore, tree root zones placed on or adjacent to the levee embankment essentially extend infinitely along the levee alignment. A root zone is represented as a "slot" rather than a disk, cone, or rectangular block. Accordingly, there is a tendency for 2D models to overestimate effects of root zones on seepage.

9.3.1 Shields and Gray

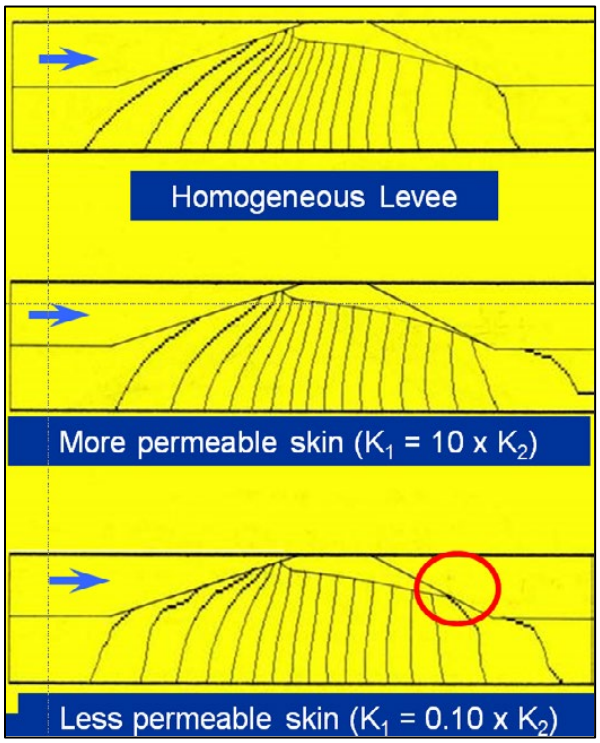
Shields and Gray (1992) used a 2D steady-state model to examine seepage patterns for a sandy levee along the Sacramento River just north of Sacramento. A relaxation technique, implemented in a spreadsheet, was used to solve finite difference equations for the flow net with waterside river stage at 0.9 times the levee height. Vegetation effects were simulated by varying the hydraulic conductivity of a 0.3-m-thick surficial layer of soil. Because definitive information about the effect of vegetation on bulk hydraulic conductivity of levee soils was not available, a sensitivity approach was used in which the bulk hydraulic conductivity for the simulated levee was varied over a range of 100. Equipotential lines[11] were computed for three cases: a homogeneous levee, one with a surface layer 10 times more permeable (bulk hydraulic conductivity, K_b) (i.e., $10K_b$) than the core, and one with a surface layer 10 times less permeable ($0.1K_b$) than the core. Little effect on waterside equipotential lines was noted, but a $0.1K_b$ surface layer elevated the phreatic surface on the landside slope and increased the seepage discharge area on the slope (Figure 9-3). This condition could lead to decreased slope stability and increased danger of seepage erosion for the simulated sandy embankment.

9.3.2 Khalilzad et al.

More sophisticated modeling that allowed coupling of transient seepage and deformation modeling using the PLAXIS model was conducted for a Delta levee near Elkhorn, California (Khalilzad et al. 2013). Scenarios similar to those used by Shields and Gray (1992) produced similar results to those produced by Shields and Gray (1992) regarding the seepage front. Variation of hydraulic conductivity for a 0.75-m-thick surficial layer indicated displacement of the phreatic surface upward on the landside levee face when the hydraulic conductivity of the surface layer was $0.1K_b$. However, this model also includes simulation of deformation as well as seepage, and the modeling indicated that horizontal deformation (e.g., slumping, bulging, shearing) at the levee toe was less for both the $10K_b$ and $0.1K_b$ surficial layers than for the "no vegetation" ($1.0K_b$) scenario. On the

[11] Lines along which water potential energy is constant. Potential energy of water at any point is the sum of the elevation and pressure head. Pressure head is the pressure divided by the specific weight of water.

other hand, the hydraulic gradient at the toe was greatest for the $0.1K_b$ surface layer. Because the modeled case was partially hypothetical, no validation with field data occurred.



Source: Shields and Gray 1992

Figure 9-3. Results of Sensitivity Analysis Examining Effects of Varying Surface Soil Hydraulic Conductivity on Seepage (Khalilzad et al.)

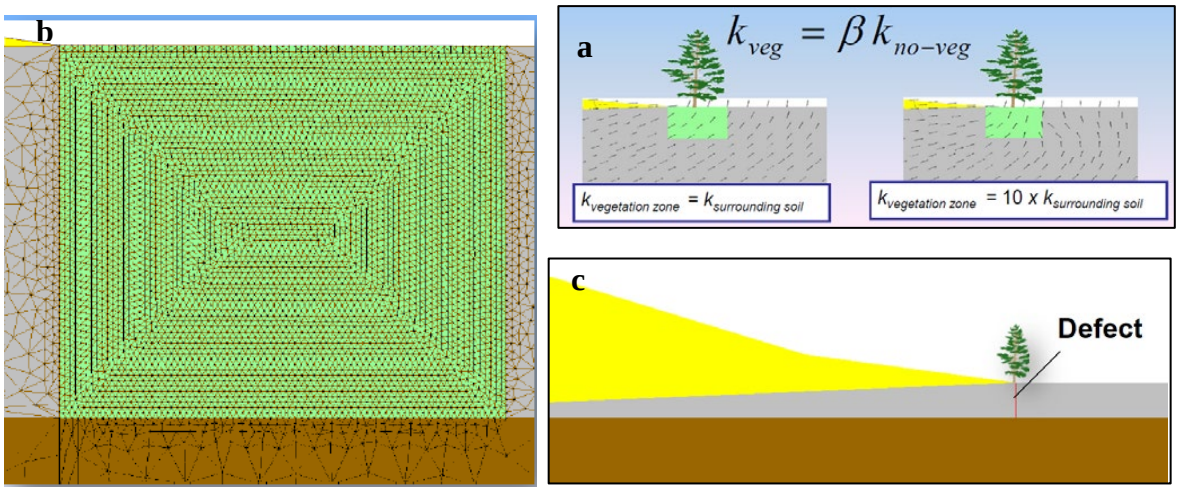
9.3.3 USACE Engineer Research and Development Center

Corcoran et al. (2011) and Tracy and Corcoran (2012) report the results of studies using the 2D seepage model SEEP2D for levees under critical transient and steady-state hydraulic loadings. Levee dimensions and soil properties were selected based on reported conditions at four sites in the western U.S. (Sacramento, California; Burlington, Washington; Portland, Oregon; and Albuquerque, New Mexico). Simulated vegetation was inserted at a variety of locations to test effects. Because the modeled cases were partially hypothetical, no validation with field data occurred. Vegetation was represented in a succession of model runs in three ways:

- Assuming that vegetation (a tree) influences a rectangular block 5 ft deep by 6 ft square (the "root zone") (Figure 9-4a). This influence was represented by changing the hydraulic conductivity of all of the model grid cells inside this block to be up to 1,000 times greater or as much as 1,000 times smaller than the surrounding soil matrix. In other words, the value of β in Figure 9-4a varied from 0.001 to 1,000. The case without trees present was represented by assigning hydraulic conductivities to all cells based on soil properties.

- Assuming that the vegetation creates a zone of very heterogeneous hydraulic conductivity. The 5-ft by 6-ft root zone was divided into 1-in cells, and the hydraulic conductivity of each cell varied from the value used for surrounding unvegetated soil by a randomly assigned β factor between 0.01 and 100 (Figure 9-4b).

- Assuming that vegetation influence is manifest as a small-diameter vertical defect in the soil blanket on the landside floodplain beyond the levee toe (Figure 9-4c). This defect allows water to move more rapidly from the permeable layer underlying the levee to the surface.



Source: Corcoran et al. 2011

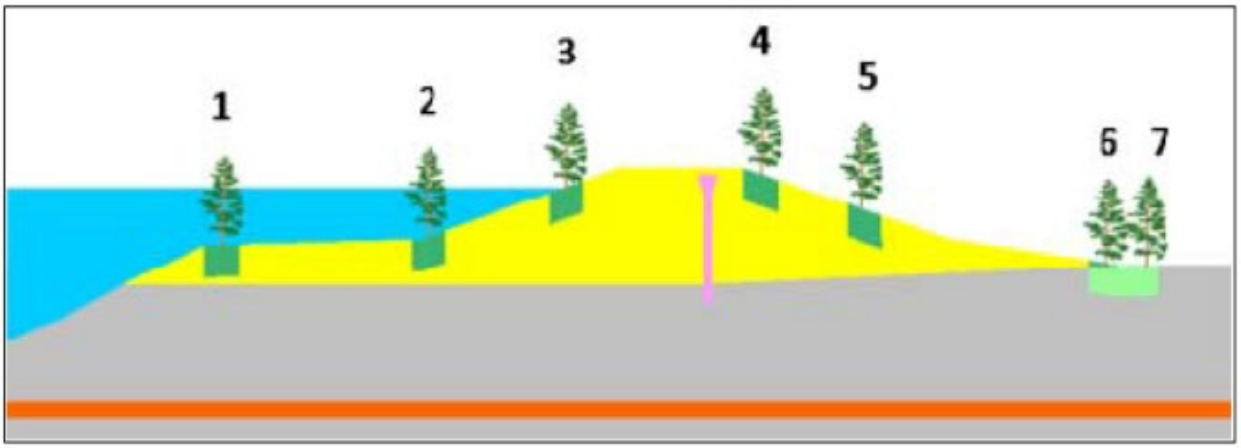
Yellow wedges in 9-4a and 9-4c represent the landside toe of the levee embankment. Green rectangles in 9-4a and 9-4b represent a 5-ft by 6-ft rectangular "root zone" where soil permeability is modified by tree roots and associated influences. Arrows represent groundwater velocity vectors. The root zone in 9-4b is subdivided into 1-in squares for random assignment of hydraulic conductivity.

Figure 9-4. Representations of Tree Roots in Two-Dimensional Seepage Models

The first two approaches were applied for single trees growing at a variety of locations on or adjacent to the levee cross section (Figure 9-5).

Simulation results were reported for each site and for each method. For the first approach, model outputs included exit gradients, pore pressure distributions, total head distributions, and seepage velocity fields. Exit gradients are of concern for initiation of piping erosion, as discussed below. It was found that the root zones generally affected only the flow field within their immediate vicinity. For example, the local hydraulic gradients and flow per unit area reflected the modified hydraulic conductivity assigned to the root zones, but the simulated root zones had virtually no influence on the overall groundwater flow field or exit gradient at the levee toe (Tracy and Corcoran 2012; Table 9-1).

The most pronounced impact on the flow path or critical gradient occurred when the tree was located at the landside toe of the levee, but this impact depended on the assumed hydraulic conductivity. Changes in hydraulic conductivity due to simulated vegetation on the riverside did not appear to affect the landside flow conditions. Furthermore, trees located on the slopes above the phreatic surface had a limited effect on seepage. The greatest effect was from trees at the landside levee toe or from trees located in a dewatered drainage ditch just landward of the levee toe.



Source: Tracy and Corcoran 2012

In this figure, blue represents water, green represents root zones, yellow represents sandy soils, gray represents clay and silt, and orange represents clay.

Figure 9-5. Schematic Levee Cross Section Showing Root Zones Corresponding to Various Tree Locations Used in Two-Dimensional Simulations by Corcoran et al. (2011)

Table 9-1. Exit Gradients (feet per foot) at Levee Landside Toe from Different Root Zone Placements and Root Zone Hydraulic Conductivities

Root Zone Location (numbers refer to Figure 9-5)	$\beta = 0.01$	$\beta = 1$	$\beta = 100$
1—Near the riverside limit of sandy stratum	0.33	0.33	0.33
2—The change in slope on the riverside	0.33	0.33	0.33
3—At water's edge on the riverside	0.33	0.33	0.33
4—Near the top of the landside	0.33	0.33	0.33
5—Midway on the steeper landside slope	0.33	0.33	0.33
6—On the toe	0.24	0.33	0.03
7—Beyond the toe	0.49	0.33	0.01

Source: Tracy and Corcoran 2012

Note: Conductivity given by $K = \beta K_b$, where K_b is base value with no vegetation.

For the second approach (macropore heterogeneity), resulting seepage velocity vectors showed relatively large flow velocities. However, the implications for piping erosion were not explored (Corcoran et al. 2011). For the third approach (vertical defect), the impact of the defect on seepage exit gradients at the levee toe was related to the thickness of the layer of low-permeability floodplain soil underlying the levee ("blanket layer"). Seepage gradients were definitely increased by the presence of the vertical defect over cases with no defects. Implications for erosion are presented below.

9.3.4 University of California, Berkeley

Cobos-Roa et al. (2012b) presented the results of numerical models of seepage through hypothetical, idealized blocks of uniform soils with various numbers of horizontal tubular voids of various numbers and lengths. The numerical experiment simulated the advance of phreatic surface through a soil block with hydraulic loading on one end (waterside) and atmospheric pressure on the other (landside). The presence of such tubular voids (holes) destabilized wetting patterns within an unsaturated soil block relative to a soil block without holes or voids. When tubular voids were connected to the waterside, the phreatic surface was displaced, and the time required for saturation was shortened for the region close to the waterside. However, the flow rates through the isolated discontinuities were low and highly dependent on the rate of flow through the soil matrix around the hole. For coarse, permeable soils, the effect of discontinuous, open gaps was negligible because of the amount and velocity of flow through the high-hydraulic-conductivity soils. Conversely, for fine, relatively impermeable soils, the effects of discontinuous open gaps was limited by the flow coming out of the soil matrix, which was relatively low. Thus, in the idealized case, the effect of tubular voids that only partially penetrated the soil mass was modest for both coarse and fine soils.

9.4 Three-Dimensional Numerical Simulations

9.4.1 USACE Engineer Research and Development Center

Corcoran et al. (2011) reported two types of 3D seepage simulations:

The first was an extension of the 2D methods described above (Tracy and Corcoran 2012) wherein the rectangular root zone was extended to become a 3D prism with uniform properties. The resulting idealized numerical levee models are essentially prismatic cross sections with trees positioned every 20 or 30 ft, depending on the assumed root zone geometry.

The second was a more sophisticated, higher fidelity approximation to a root geometry reconstructed from LiDAR scans taken from a fully exhumed tree at a test site in Vicksburg, Mississippi, based on deformation analysis as described by Kees et al. (2008). Because of inherent limitations in the 3D model, it was applied to create parameter sensitivity studies for assessment of the 2D results and insight into governing processes. Seepage-induced deformation models combine seepage and slope stability analyses and represent the state of the art (e.g., Corcoran et al. 2011, Kees et al. 2012, Khalilzad et al. 2013).

For the first approach, the “root zone” prism was subdivided into very small elements, and the hydraulic conductivity assigned to each element was randomly varied across several orders of magnitude centered on a value assumed typical of the unvegetated state ($\beta = 1$). The large number of elements, wide variation in hydraulic conductivity, and nonlinearity of the governing equations created computational difficulties as described by Tracy and Corcoran (2012). Next, 3D models were developed for two sites (Sacramento and Burlington, Washington) using selected “worst-case” scenarios and soils and geometry data from existing sources. Three woody

vegetation zones located at the toe (landside toe, Sacramento; riverside toe, Burlington) and positioned 20 ft apart were considered.

As in the 2D simulation, it was found that preferential flow associated with the root zone with heterogeneous hydraulic conductivity had velocities much greater than for the uniform, unvegetated case. In general, the effect of a single tree in 3D flow on levee performance was smaller than in a 2D flow field. Large local increases in pore pressure gradients may occur if the root system is assumed to cause large decreases in hydraulic conductivity near the surface. Large local increases in seepage velocity may occur if the root system is assumed to cause large increases in hydraulic conductivity. Changes in pore pressure caused by differences in hydraulic conductivity of less than an order of magnitude are small, especially if 3D geometries are considered.

Overall, 3D models indicated that root-system effects on the hydrodynamics were local (confined to the root system). Local 3D effects were observed in the flow field around the root zones, but the resulting 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. Corcoran et al. (2011) stated that the lack of impact on large-scale seepage characteristics validates the use of 2D seepage models for determining seepage behavior at the large (levee) scale, but as noted above, 2D models tend to overestimate seepage exit gradients relative to those predicted by 3D models. Evidently the similarity of 2D results to the more realistic 3D simulations was seen to validate the former.

9.4.2 University of California, Berkeley

Cobos-Roa et al. (2012b) report development of a 3D levee seepage model based on the SEEP3D code and application to the “wetting test 1” described in Section 9.2, “Field Experiments,” and depicted in Figure 9-1. This study is distinct among those presented here as it attempted to reconstitute actual field data. The documented soil conditions were approximated in the model by using a lower hydraulic conductivity value in stump regions and representing the large mammal burrow as a tubular region with very high conductivity. The model appeared to capture the general trend of the observed data (fast saturation around burrow, slower saturation around stump). Seepage between the two trenches was dominated by flow in the mammal burrow, as in the field test.

9.5 Linking Seepage Simulations to Piping Predictions

Levee seepage is not a bad thing in and of itself, but it can be extremely serious when seepage results in subsurface (internal) erosion. “Piping” is the term used to refer to several internal erosion processes driven by groundwater seepage (Wilson et al. 2012). Piping processes have both positive and negative feedback mechanisms that create a system that has defied efforts by many workers to develop definitive predictions or simulation tools. Erosion of the walls of a void or pipe may produce sediment that clogs the downstream openings and damps the erosion process, or it may enlarge the pipe quickly enough to transport all sediments and capture more seepage flow. Because definitive prediction of seepage-driven erosion (“piping”) involves

complex feedback, it is at or beyond the current state of the art (Corcoran et al. 2011). Basic work in piping prediction has focused on determining the magnitude of hydraulic gradients at points where seepage exits the levee embankment on the landside slope. Generally, upward gradients in excess of 0.9 to 1.0 foot per foot (ft/ft) are judged to be hazardous, although the exact value varies with soil erodibility (e.g., Duncan 1999).

A simple capillary model to describe the process of clay dispersion and piping was developed by Khilar et al. (1985) and used to establish a predictor for the onset of piping that involves (1) the porosity and initial absolute permeability of the soil, (2) the critical shear stress, and (3) the hydraulic gradient. Glynn and Kuszmaul (2004) produced an empirical model for predicting foundation piping from underseepage for levees along the middle Mississippi River. The model was a logistic regression that predicted whether piping was likely or unlikely based on the aquifer sand grain size, the thickness of the confining layer, the presence and alignment of adjacent swales, and the history of previous piping.

9.5.1 USACE Engineer Research and Development Center

Analyses of seepage using the vertical defect approach for simulating macropores caused by roots described above were conducted for levee sites in Burlington, Washington; Portland, Oregon; and Albuquerque, New Mexico. The “toolbox” developed by Schaefer et al. (2010) was used by Corcoran et al. to infer the consequences of the seepage that was predicted by the numerical model with the “vertical defect.” Based on these analyses, the probability of initiation of internal erosion was found to be negligible for cases with woody vegetation at the landside toe of the levee for the Burlington and Portland sites. The results for Albuquerque yielded a safety factor slightly higher than 1.0, but the probability of internal erosion occurring ranged from near 0 to 0.25.[12] Tracy and Corcoran (2012) reported an internal erosion probability of 1.0 for a hypothetical levee with a 5-ft blanket thickness. The report by Schaefer et al. (2010) has never been released in final form, nor has the method it recommends been published in the referenced literature.

9.5.2 University of California, Berkeley

Piping processes were not simulated in modeling studies described by Cobos-Roa et al. (2012b), but inferences were drawn based on seepage rates through voids. Modeling indicated that flow rates and flow velocities through isolated discontinuous tubular voids were low and highly dependent on the rate of flow through the soil matrix around the void. Therefore, piping potential from discontinuous voids was judged to be low. On the other hand, piping potential from continuous voids or holes (e.g., mammal burrow networks that penetrate the entire levee embankment such as those documented by Cobos-Roa et al. 2012b) is a function of hydraulic head (river level relative to the elevation of the landside hole entrance) and the erodibility of the soil surrounding the continuous void.

[12] In a case such as this one, the Schaefer et al. (2010) procedure produces a range of probability of seepage as its output.

9.6 Data Gaps

Few field data are available regarding levee seepage and piping in the vicinity of living or dead trees. Predictions of pipe formation and enlargement are at or beyond the present state of the art. Full examination of the influence of tree roots requires 3D simulation; however, computer programs for this type of simulation are not sufficiently developed for widespread application at present. Such programs require specialized expertise and significant resources for acquiring input data for a given site, constructing and running the models, and interpreting results.

9.7 Points of Scientific Debate

Forests tend to display higher levels of soil permeability than grasslands or maintained turf, but similar effects of trees on levee slopes have not been documented. Soil structures such as levees are never uniformly homogeneous due to bioturbation, shrinkage cracks, hydraulic fracturing, and construction events (e.g., changes in soil properties attributable to excavation, fill, compaction, loading, or unloading). Unengineered fills such as many of the levees in central California are particularly heterogeneous, with a wide range of macropores dominated by animal burrows. The importance of void volume defects created by trees relative to those created by other processes is controversial.

The effects of living and dead trees on soils are local and complex and are quite difficult to simulate in numerical models. Models are abstractions of reality, and decisions based on model outputs require some amount of subjective interpretation. The 2D model described by Shields and Gray (1992) was entirely hypothetical, so there was no calibration or validation with field data. Transient hydraulic loading was represented by steady conditions; the authors argued that this was a good approximation for the site in question. Hydraulic conductivities in real soils tend to be spatially heterogeneous and, as noted above, dominated by flow through macropores. Thus, a uniform conductivity for the top 0.3 m of soil is unlikely for levees unless they are similar to the research levee described by Lammeranner (2012). That research levee likely has such a pattern because of the limitation of rooting depth caused by planting shrubby willows in brush layers and compacted levee soils.

Models described by Corcoran et al. (2011) used three approaches to assigning hydraulic conductivity to regions influenced by tree roots (Figure 9-4 and associated text). The first approach for assigning soil hydraulic conductivity does not consider the influence of macropores, as a uniform hydraulic conductivity value is assigned to the root zone. Despite wide reports of modified (high) hydraulic conductivity for natural forested slopes, attempts to relate hydraulic conductivity to vegetation cover on levees have failed to demonstrate a consistent pattern (Corcoran et al. 2011, Khalilzad et al. 2013). Some of the hydraulic conductivities assigned to various soil layers for simulation of the Sacramento levee (Corcoran et al. 2011:Table 1, Vol. III) differ considerably from those recommended by the California Science Team (2010).

Even if roots modify the hydraulic conductivity of levee soils, their effects would be better represented by modeling that reflects real-world spatial distributions of roots. However, both the first and second approaches described above assume that the presence of a tree is manifest by modification of soil properties within a 5-ft by 6-ft zone. This assumption is not consistent with new studies of root biomass spatial distributions, which show that root mass declines exponentially with distance from the tree (see Chapter 2).

Finally, the third approach assumes a worst-case scenario in which a root creates a continuous vertical void from the ground surface through a floodplain blanket layer. To the knowledge of the author of this report, no such voids created by roots have been reported in the literature.

9.8 Potential Implications for Levee Vegetation Management

Model simulations indicate that most pronounced effects of enhanced seepage on levee integrity occur when a zone of elevated hydraulic conductivity occurs at the landside levee toe. However, both model simulations and field observations underscore the fact that animal burrows tend to dominate levee seepage even when trees are present. Sophisticated 3D models that simulate deformation of soil continua offer high temporal and spatial resolution and are promising but are currently too complex for routine application outside of a research context.[13]

[13] Research models are typically formulated for a limited number of highly specialized users and often require large amounts of highly detailed input to describe the spatial and temporal variation in model boundaries and properties. These models are useful for deepening the understanding of a certain type of system, but they are not useful for widespread application to real-world problems by practicing engineers and scientists rather than research personnel. Application models typically feature thorough documentation; powerful user interfaces; default values for key inputs or menus to assist in the selection of key inputs; and simplified or abstracted expressions that capture only the essential temporal and spatial variation in system properties, both in input and output.

10 Effects of Trees on Levee Slope Stability

Abstract
Levees sometimes fail when slopes collapse or slide. These slope failures generally occur whenever the driving forces (e.g., the weight of the soil or differential pore-water pressure) exceed resisting forces provided by embankment soils. Additional driving forces may include dynamic forces from earthquakes and vehicle traffic. Woody vegetation may affect the stability of levee slopes by increasing soil strength from root effects, modifying moisture profiles, or transferring loads from wind or tree weight. Geotechnical models used to assess slope stability may be modified to include the effects of vegetation by uniformly increasing soil cohesion or hydraulic conductivity in root zones or by more sophisticated approaches. Models may be two- or three-dimensional (2D or 3D). Early work comprised 2D models with simple representations of root effects. An early study based on a sandy levee near Sacramento, California, found that vegetation increased the factor of safety (Fs) from less than 1 (probable failure) to greater than 1 (probable stability). A subsequent 2D simulation of hypothetical levees typical of those along the Sacramento River with a range of vegetation types, locations on the levee cross section, and hydraulic conditions was conducted with a model that offered more sophisticated, realistic treatment of root effects. Of all scenarios considered, only one with no vegetation produced Fs less than 1. More recent studies of effects of trees on levee slope stability have included 2D analyses of levees based on three sites in the western U.S. Fs was computed for deep-seated failure arcs for levees with single trees positioned at various places on the cross section. These studies used a seepage model to predict the location of the phreatic surface under worst-case hydraulic loadings. Root zones for individual trees were simulated as 5-ft by 6-ft rectangular elements with uniformly increased cohesion and by four additional large roots extending outside the rectangular zone. In general, effects of trees on Fs were slight (less than10%) and usually positive. Simulation of wind loads was found to be inaccurate. Another set of 2D studies based on an instrumented levee in central California with a single midslope tree included sensitivity analyses for eight key parameters. Addition of a tree increased Fs except when wind loadings were quite high, but representation of wind loads was found inadequate. A 3D numerical model study of hypothetical cases of the effects of trees on levee seepage and slope stability is also reviewed. This study was a parametric analysis providing a basis for additional research but not management solutions.

10.1 Relevance to Levee Performance

Levees sometimes fail when slopes collapse or slide. These slope failures generally occur whenever the driving forces of gravity or pore-water pressure exceed resisting forces provided by embankment soils. Woody vegetation is believed to affect slope stability in four main ways:

- mechanical reinforcement by the roots of woody vegetation,
- soil arching in regions between trees,[14]

[14] When soil masses in regions between trees begin to slide, they experience a stabilizing shearing force with the soil masses on either side that are supported by the trees. This “arch effect” means that stabilization effects of trees are distributed more widely on the slope than otherwise.

- enhanced infiltration/evapotranspiration associated with vegetation,[15] and
- additional loading from the weight of trees and from wind forces on aboveground portions of trees transferred through roots to the soil.

It should be noted that removing trees from levee slopes has impacts as well: studies of forest slopes indicate that decaying roots gradually cease to provide mechanical reinforcement and may facilitate infiltration and seepage. An association between clear-cutting of forested hillslopes and slope failures has been widely noted (Gray 2009d), and woody vegetation contributes to streambank slope stability (Simon and Collison 2004, Pollen-Bankhead et al. 2009).

However, it should be noted that hydraulic loading of hillslopes and streambanks is different than that for levees. Hillslopes are loaded by precipitation and snowmelt, and typically have the lowest heads (pore-water pressure) at the top of the slope. Levees are loaded by riverside flooding as well as precipitation. The distribution of soil moisture and pressure head relative to the slope is influenced by lateral as well as vertical movement of floodwaters. Levee slopes also differ from typical watershed hillsides in terms of their length and inclination, canopy densities, and underlying geology. Forested hillslopes typically support higher densities of trees than treed levee slopes.

Despite these differences, it is worth noting that Bachmair et al. (2012) found that the hydrologic behavior of hillslopes at a site in the Black Forest of southwestern Germany was strongly governed by vegetative cover, with infiltration under grass cover much more rapid than for forest, perhaps because of the higher frequency of animal burrows on the grassed slopes.

10.2 Analytical Techniques

Failure of slopes large enough to support trees is difficult to replicate experimentally (but see http://en.wikipedia.org/wiki/IJkdijk), and data from failures of instrumented prototype slopes with woody vegetation are nonexistent (Sonnenberg et al. 2012). Thus, mathematical analyses of slopes using input parameters from field or lab measurements of soils and roots are quite important for prediction, research, and design.

Soils tend to fail in shear[16]; roots (fibers) that cross potential failure planes act as tensile inclusions (reinforcing fibers) that directly resist shear and/or that increase shear resistance by

[15] Soil strength is sensitive to soil moisture. Up to a point, drier soils are stronger than wetter soils. Woody vegetation can foster drier conditions in soils through evapotranspiration or can foster higher moisture levels by creating macropores that increase infiltration. See Simon and Collison (2004) for more information about the hydrologic effects of vegetation on slope stability.

[16] A shear failure is a break in a block of soil produced by sliding or slipping along a plane that is parallel to the direction of the force.

increasing the normal stress[17] on the failure surface. Larger roots that cross the failure surface can act as structural elements or "shear pins" that restrict movement along a failure surface.

Simulations of the effects of vegetation on slope stability depend on analytical or numerical models of soil reinforcement by vegetation. Wu (2013) classified existing approaches as either macro models or soil-vegetation interaction models. Macro models consider the root-impregnated soil as a homogeneous material whose properties may be determined by tests on the rooted soils. This type of model is best suited for situations where the dimensions and spacing of roots are small, because tests for extremely large soil specimens needed to produce fairly homogeneous conditions for large roots are not practical. The soil-vegetation interaction models are better suited to situations where roots are large and not uniformly distributed in the soil. A wide variety of soil-vegetation interaction models have been formulated (Wu 2013), but are not widely used in practice. Many of these (both 2D and 3D) are finite element codes that treat the soil as a plastic (deformable) media (e.g., Mickovski et al. 2011, Kokutse et al. 2006).

The contribution of roots to soil strength may be measured in the lab using live plants or soils impregnated with inclusions (e.g., inert fibers) intended to simulate roots (Bransby et al. 2006, Mickovski et al. 2008). Lab tests include direct shear tests, root pullout tests, and centrifuge tests (Sonnenberg et al. 2012, Wu 2013). Pullout tests are also performed in the field. Direct shear tests are of limited value in slope stability problems because the failure plane and orientation are dictated by the testing apparatus, while slope failure planes form along zones of weakness (Sonnenberg et al. 2012). Additional information regarding root contributions to soil strength is found in Chapter 4, "Root Strength."

Slope stability is strongly influenced by soil moisture and groundwater levels (Simon and Collison 2004, Sonnenberg et al. 2012), and analytical techniques are limited by the realism of their simulation of spatial and temporal variation in matric suction[18] and pore-water pressure. Slope stability analyses are often preceded by and dependent on the outcome of seepage analyses.

10.3 Two-Dimensional Numerical Simulations

10.3.1 Early Work

Shields and Gray (1992) assessed the effect of woody vegetation on stability of sandy levee slopes using infinite-slope and circular-arc analyses. Effects of vegetation on soil strength and hydraulic conductivity were considered, but forces on the slope caused by the weight of vegetation or wind loads on vegetation were not considered. The effects of vegetation on soil moisture profiles and seepage patterns also were not considered. Levee foundations (floodplain soils) were assumed to be impermeable. Vegetation influence was simulated by increasing soil

[17] Force per unit area that acts perpendicular to the plane to which a force has been applied.

[18] The suction exerted by the soil material (matrix) that results from the combined effects of adsorption and capillarity due to the soil matrix. Matic suction is a negative pressure that causes water to flow from wetter soil (low matric suction) to drier soil (high matric suction).

cohesion by an amount proportional to the RAR derived from field measurements using the profile wall method as described in Chapter 2 of this report. Model inputs (soil characteristics, levee geometry, worst-case hydraulic loading) were based on the field site along the Sacramento River north of Sacramento, California. For the infinite-slope analysis, the RAR (and thus the contributed cohesion) did not vary with depth below the surface, and the seepage angle was assumed equal to the slope angle. The Fs increased from 0.6 to 8.8 as RAR increased from 0.01% to 1%. Circular-arc analyses were conducted with the modified Bishop method of slices and assumed a sudden drawdown condition. For the vegetated case, RAR was computed using a regression formula that was a weak function of depth below the ground surface. The Fs varied from less than 1 for the case with no vegetative influence (RAR = 0) up to 1.1 for the case with roots and a deep (approximately 1 m) failure surface. To summarize, the simulations indicated that the sandy levee was unstable without vegetation and increasing amounts of vegetation (and associated root reinforcement) produced increasing levels of stability.

10.3.2 Follow-on Work and Application of Fiber Bundle Model

Norris and Greenwood (2006) reviewed available data and applied a macro model approach ("routine limit equilibrium stability analysis"). They concluded that the roots of "appropriately planted and maintained vegetation" are likely to increase the Fs of potential shallow slip surfaces by about 10%.

Work by Shields and Gray (1992) was strengthened by Pollen and Shields (2007), who used a 2D model originally developed to assess streambank stability, the USDA Agricultural Research Service Bank Stability and Toe Erosion Model (BSTEM). The version of BSTEM used simulated wedge-type slope failure under static loading and a horizontal phreatic surface. As before, the influence of vegetation was simulated using the "macro approach"—increasing soil cohesion, but by constant amounts within the root zone for each of three different types of vegetative cover as shown in Table 10-1. In an improvement over the work by Shields and Gray (1992), an FBM (Thomas and Pollen-Bankhead 2010, Pollen-Bankhead et al. 2013) was used to assess mobilization of the root contribution to soil strength. The earlier approach used by Shields and Gray (1992) assumed simultaneous mobilization of all root contributions to soil strength, which implies that all roots break simultaneously. This assumption leads to overestimation of the contribution of roots to slope stability (Pollen-Bankhead et al. 2013), as does the assumption of root breakage rather than pullout (Sonnenberg et al. 2012).

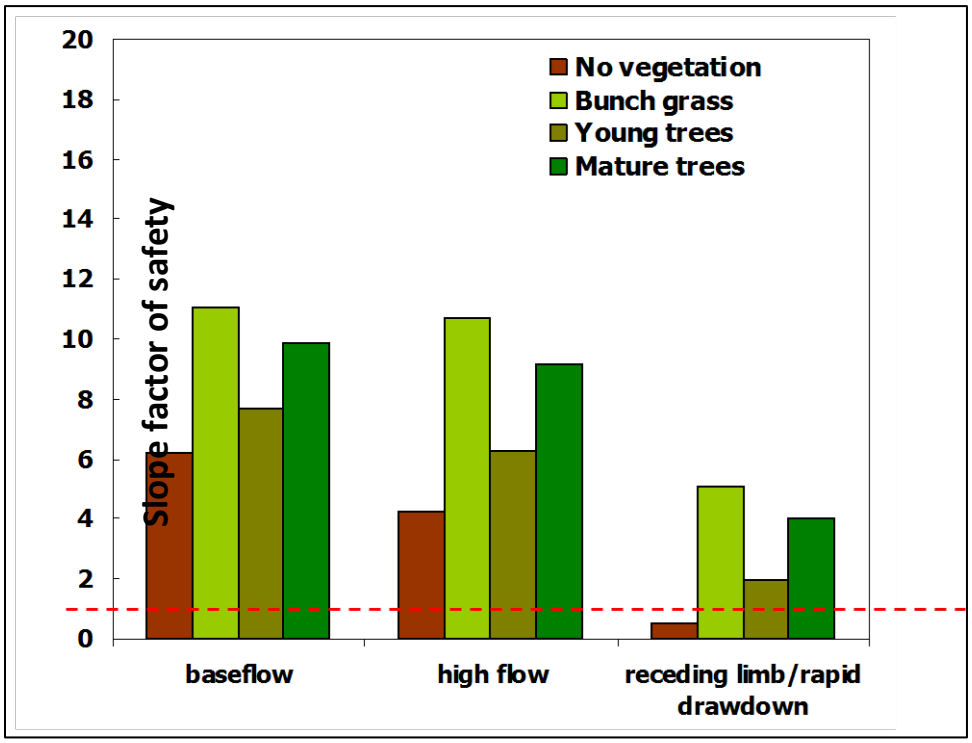
Table 10-1. Characteristics of Vegetated Surface Layers Simulated by Pollen and Shields (2007)

Vegetative Cover	Rooting Depth, m	Root Contribution to Soil Cohesion, kPa
None	N/A	0
Bunch grass	0.5	15
Young trees	1.0	3
Mature trees	1.0	20

Source: Pollen and Shields 2007

Notes: kPa = kilopascals; m = meters; N/A = not applicable. Soil was silty sand with low cohesion (0.84 kPa).

Model simulations were run by Pollen and Shields (2007) to compute the Fs for all four of the cover types shown in Table 10-1, with each cover type placed at three different locations: on the levee crown, on the waterside slope, and on both the levee crown and the waterside slope. Each of these 12 scenarios was subjected to three different hydraulic loadings: both river stage and water table low ("baseflow"), both river stage and water table high ("high flow"), and river stage low and water table high ("receding limb/rapid drawdown"). The results for vegetation on the waterside slope indicated that vegetation was essential to slope stability under worst-case (rapid-drawdown) loading (Figure 10-1). Bunch grass and mature trees tended to produce a greater Fs than young trees.



Source: Pollen and Shields 2007
Note: Red dashed line indicates factor of safety = 1.0.

Figure 10-1. Factors of Safety for Waterside Levee Slope under Four Different Types of Cover and Three Different Static Hydraulic Loads

10.3.3 Streambank Stability Analyses by Simon and Others

Simon and Bankhead (2012) have produced a large body of work describing and quantifying processes important to streambank stability. They note the beneficial influence of vegetation on slope stability through evapotranspiration (reducing pore-water pressure and increasing soil strength through matric suction), adding reinforcement to soils through roots, and reducing fluid shear experienced by soils exposed to river flow. They have quantified these effects, and this work has been codified in a 2D model (BSTEM) for assessing streambank stability that uses an FBM approach to quantifying the contribution of roots to soil strength (Midgley et al. 2012). The BSTEM model has been widely applied. For example, Pollen-Bankhead et al. (2009) analyzed

4-m-high streambanks at a site in New Mexico using the FBM approach and found that the Fs for vegetated banks ranged from 1.42 to 1.52. Removal of the influence of vegetation in the model produced safety factors ranging from well below 1.0 to 1.23 for the same banks under the same conditions.

Simon and Bankhead (2012) argue that their BSTEM model may apply to assessment of levee slope stability if one accounts for the different moisture profile produced by hydraulic loads (higher water surface elevations) on the waterside of levees. The report by Pollen and Shields (2007), described above, is an application of an earlier version of the BSTEM model to levees.

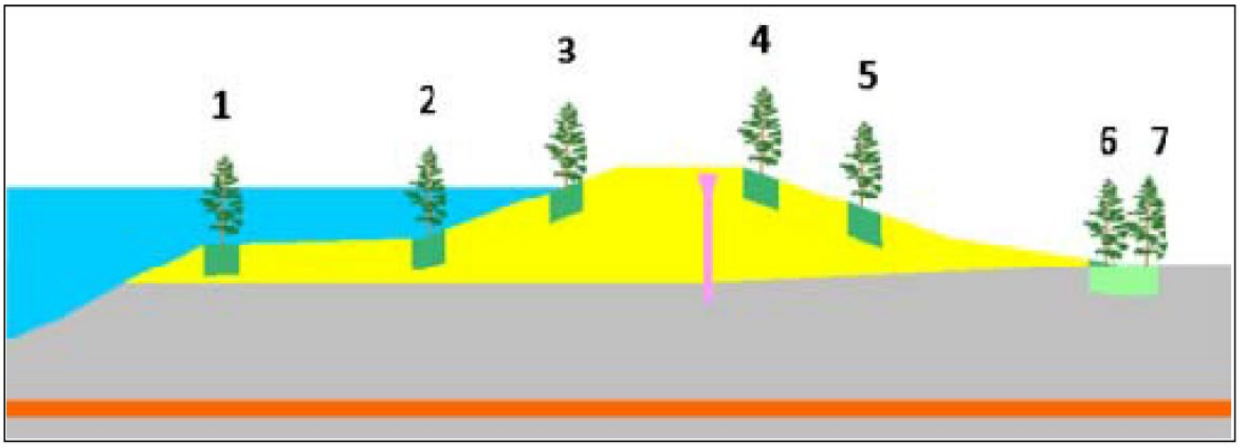
10.3.4 USACE Engineer Research and Development Center

As described in Chapter 9, "Effects of Trees on Seepage and Piping in Levees," the SEEP2D model was used by Corcoran et al. (2011) to predict the location of the phreatic surface under worst-case loadings with and without woody vegetation. Seepage model outputs were provided as input to the 2D slope stability models, which were based on the UTEXAS4 software. Corcoran et al. (2011) present 2D slope stability analyses for levees located at Sacramento, California; Burlington, Washington; and Albuquerque, New Mexico. Because of time limitations, only pore pressures for the seepage model results for $\beta = 100$ (soil hydraulic conductivities 100 times those observed in the field) were used in the slope stability analyses. As was done for the seepage analyses, the slope stability models "with vegetation" considered single trees at several locations on the levee profile.

The contribution of roots to soil strength was simulated in two ways. First, the root zone under each simulated tree was assumed to be a rectangular area 5 ft deep by 6 ft long (see green quadrilaterals in Figure 10-2), and soil cohesion was increased in this zone. Typical values of cohesion for sands were increased up to about 50 psf (2.4 kPa) to account for roots, and typical values of cohesion for clays (~20) were increased up to about 100 psf (4.8 kPa) following data tabulated by Norris and Greenwood (2006) (Harder 2012d). (Typical values for cohesion for sands without root effects are near zero, and typical clay cohesion values vary from 20 to 100 psf [1.0 to 4.8 kPa].) Second, four "reinforcing roots" were postulated for each tree as shown in Figure 10-3: two in the upslope direction and two in the downslope direction.

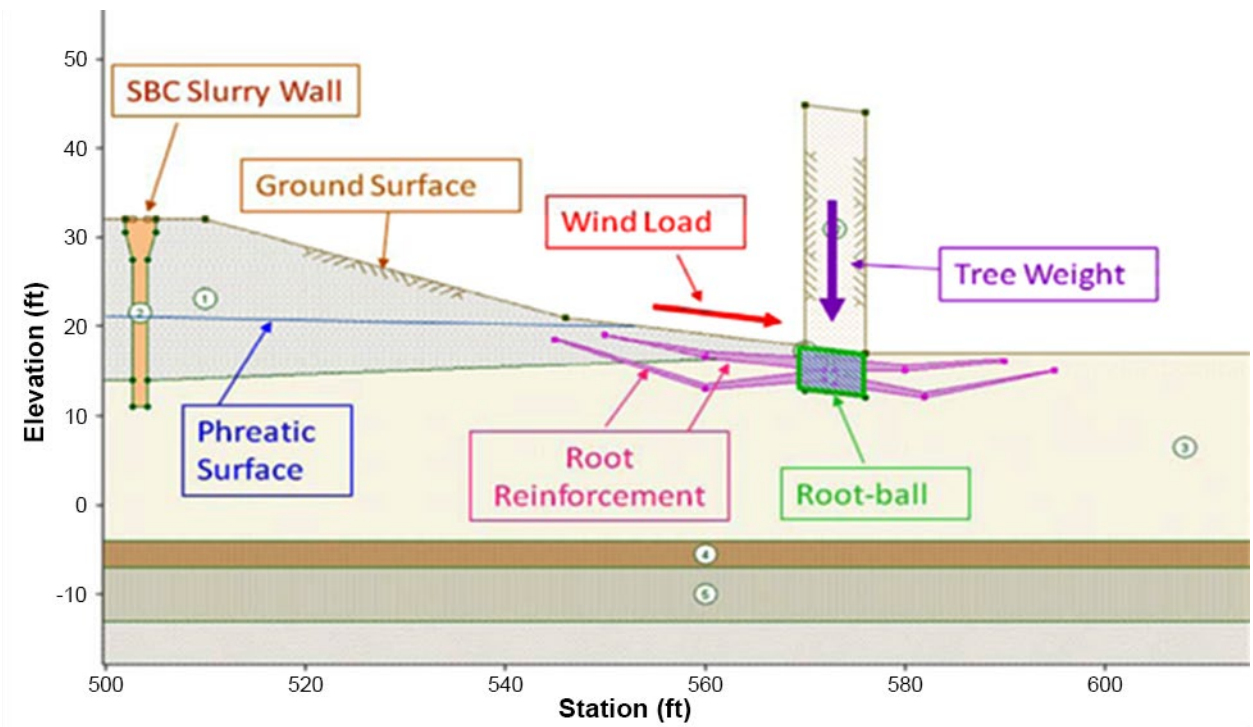
The UTEXAS4 model has a built-in automated search routine in which a floating search grid is used to examine all possible rotational failure arc locations. Because this approach always produces a shallow, local failure circle for levees built with sandy, cohesionless soils, the search routine was limited to failure arcs passing through one of three points as shown in Figure 10-4.

Differences in factors of safety caused by the presence of trees tended to be small ($\pm$0.1) and varied with tree position: trees on the upper part of the slope decreased the Fs because they added weight, while trees at the levee toe increased the Fs because of the reinforcing effects of the roots and the increased counterweight effect of the tree on slope movement. Impacts of landside trees on Fs were generally greater than for waterside trees. In the absence of wind loading, none of the modeled conditions resulted in Fs less than 1.47 for the Sacramento levee, and vegetation impacts on Fs ranged from -1% to 10% for the waterside and from -6% to 8% for the landside. Wind loads greater than or equal to 60 mph produced Fs less than 1.0 for the Sacramento levee if the tree was



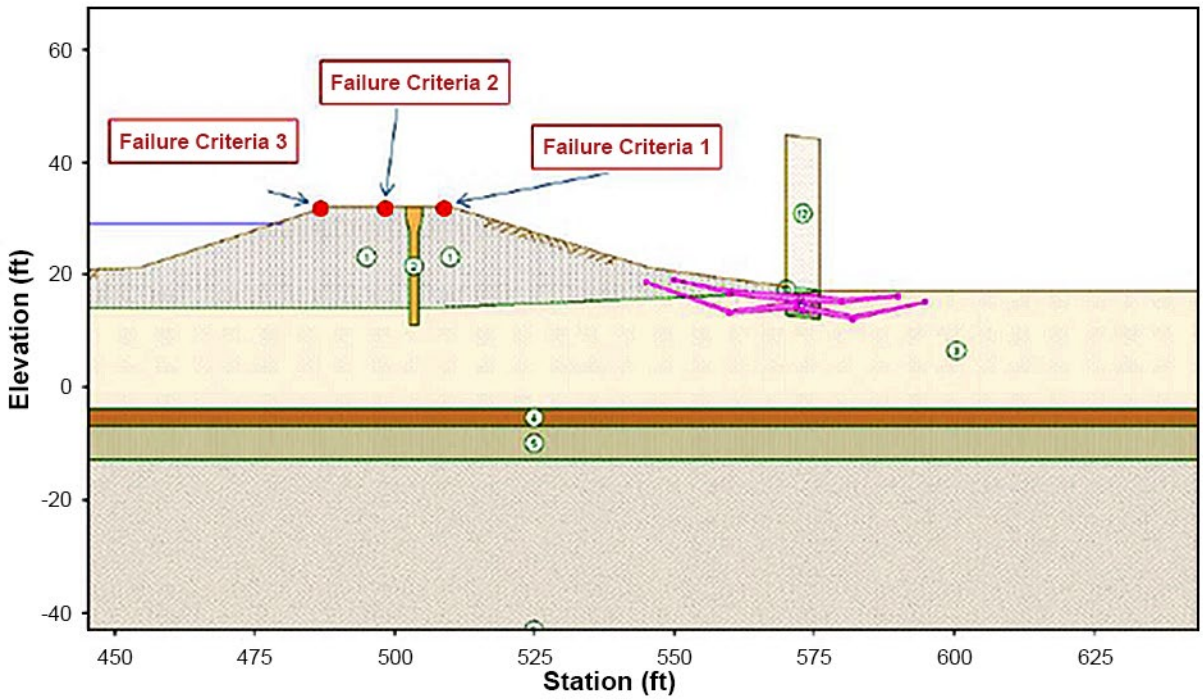
Source: Corcoran et al. 2011

Figure 10-2. Tree Locations for Two-Dimensional Seepage and Slope Stability Analyses



Source: Corcoran et al. 2011

Figure 10-3. Definition Sketch for Two-Dimensional Model for Simulation of Effects of Trees on Levee Slope Stability



Source: Corcoran et al. 2011

Note: The UTEXAS4 software search routine was constrained to failure arcs passing through one of three red points.

Figure 10-4. Three Failure Criteria Used for Two-Dimensional Slope Stability Analyses by Corcoran et al. (2011)

positioned at the top of the slope. The Burlington levee was unstable (Fs less than 1.0) for water levels at the levee crest both with and without trees, although the Fs with trees was generally higher. The addition of wind loads did not lower computed Fs below 1.0 for the Burlington levee. Computations for the Albuquerque levee showed that trees located at the landside toe would reduce Fs from about 2.3 to 2.0.

Additional computations using much higher values for root reinforcement inputs were reported by Wibowo and Corcoran (2013). These computations increased the Fs in 2D simulations of one levee from about 1.4 to a range of 1.5 to 1.6 or by 1% to 6%, depending on the details of the case.

10.3.5 University of California, Berkeley

Shriro et al. (2012) presented the results of a simulation of stability of a California Delta levee (Twitchell Island) with a tree growing at midslope. The levee was heavily instrumented and experimentally loaded by excavating a trench along the levee crest and filling with gravel and water. Seepage and stability analyses were run using the SEEP/W and SLOPE/W software programs, which produce standard limit equilibrium (Fs) results. Sensitivity analyses were run by varying key inputs as shown in Table 10-2.

Wind loads were found to exert a strong influence on Fs when wind speeds were exceptionally high (39 mph) and directed upslope. However, in agreement with Corcoran et al. (2011), Shriro et al. (2012) noted that the 2D models were not able to accurately represent impacts of wind loading on the soil mass supporting the tree. In addition, the software cannot simulate tree windthrow, which would unload the soil mass before mass failure when imposed drag forces exceeded the breakage or windthrow threshold of the tree as described in Chapter 7 of this report.

When 2D analyses were adjusted for 3D effects by mass-averaging results for several 2D sections for a segment of levee with and without a single midslope tree, the presence of the tree shifted the Fs upward from 2.5 to either 2.8 or 3.1, depending on the mass averaging scheme that was employed. Because trees are clearly 3D (i.e., their root zones do not extend infinitely in the direction of the longitudinal levee centerline), some type of adjustment of 2D inputs is required for realism. Conversion of the results of a 2D slope-stability analysis to 3D (and thus real-world) conditions is difficult and sometimes controversial (Harder 2012d).

Table 10-2. Results of Two-Dimensional Simulations and Sensitivity Analyses Based on Twitchell Island Levee

Parameter or Model Feature	Importance	Change in Parameter	Associated Change in Fs
Friction angle of silt	Moderate	29 to 32 degrees	2.5 to 2.3
Cohesion of silt	High	0 to 100 psf	2.3 to 3.6
Sustained high-water table	High	No load to water in trench at levee crest	3.6 to 2.5
Root zone permeability	Low	5×10^{-6} to 5×10^{-5} ft per second	2.5 to 2.4
2D assumptions on tree loading—width over which tree weight is distributed	High	3 to 40 ft	1.4 to 2.5
Reinforcing assumptions—representing roots as anchors extending into levee from trunk	Moderate	1 to “multiple” anchor roots	1.4 to 2.6
Reinforcing assumptions—representing roots as zones of elevated cohesion	Moderate	0 to 300 psf	1.4 to 1.6
Wind load applied from toe toward crest	Hard to say whether this affects global stability of embankment or just rootwad	0 to 39 miles per hour	1.4 to 1.0
3D estimate based on mass averaging Fs for 2D sections with and without midslope tree present	Moderate	No tree to one tree	2.5 to 3.1

Source: Shriro et al. 2012
Notes: 2D = two-dimensional; 3D = three-dimensional; Fs = factor of safety; ft = feet; psf = pounds per square foot

10.3.6 European Work

Schwarz et al. (2010) note that 2D slope stability analyses often fail to consider the "lateral" reinforcement effects of vegetation (trees) because root reinforcement effects are included as apparent cohesion or direct reinforcement due to roots crossing the failure plane, and failure planes in 2D models are constrained to lie in the plane of the model. Roots that grow lateral to this plane may also resist movement but are not represented in the 2D model. Although their work strictly considers only natural hillslopes, Schwarz et al. (2010) provide an interesting approach to scaling up the kinds of 2D models described above to an entire hillslope with up to 1,000 trees distributed randomly or in any prescribed fashion. Empirical models are used to predict the statistical distributions of root sizes, locations relative to tree stems, and mechanical behavior across an entire slope. These distributions are then used to create maps of reinforced soil strength. In this modeling effort, slope failures are shown to form along continuous regions of weak root reinforcement. Schwarz et al. (2010) concluded that large areas free of trees were found to be most prone to landsliding.

10.4 Three-Dimensional Numerical Simulations

Because trees are 3D, using 2D models to examine the effects of trees on levee slope stability is difficult. A key point is dividing loads and strength contributions of trees to realistically represent tree spacing. Douglas et al. (2013) evaluated 65 sites on pastoral hillslopes in New Zealand and found that even very widely spaced trees had been effective in reducing landslide occurrence. Although 3D simulations are not without their own liabilities, they offer promise for more realistic simulation of the effects of trees. For example, Kokutse et al. (2006) used 3D simulations to show that three trees located at corners of a 5-m equilateral triangle increased the hillslope Fs by 20% to 30% over a slope without trees. A higher Fs was associated with trees with taproot-type architecture while lower values were associated with heart- or plate-type architectures.

10.4.1 USACE Engineer Research and Development Center

In an American Geophysical Union abstract, Farthing et al. (2011) note the need for 3D simulation to fully understand the impact of vegetation on levee performance:

> The complexity of the physical processes, material heterogeneity and inherent three-dimensionality put such problems outside the range of traditional methods of analysis. Specifically, seepage and stability analysis for engineered levees is typically carried out on vertical cross-sections using steady-state subsurface flow and limit-equilibrium or semi-empirical based approaches for soil mechanics. However, vegetation can generate local modifications in the root zone that lead to genuinely three-dimensional behavior, while the temporal scale of flooding events and range of soil deformations possible make steady-state or equilibrium approaches inadequate.

The abstract by Farthing et al. (2011) states that the authors were presenting analyses of levees that were capable of simulating variably saturated flow and elastic-plastic deformation using

fully 3D, nonlinear continuum mechanical models. The abstract also states that the report includes "a verification and validation test set….[which] allows comparison to field data and traditional analytical methods." Unfortunately, no publication of these results has been found.

Corcoran et al. (2011) described 3D simulation of levee tree effects for levees at two field sites: Sacramento, California, and Burlington, Washington. High-resolution 3D seepage and stability analysis was performed upon selected "worst-case" scenarios. The 3D model featured the geometry developed for the 2D simulations described above, modified to include three woody vegetation zones located at the toe (landside toe, Sacramento; riverside toe, Burlington) and positioned 20 ft apart. Local 3D effects were observed in the seepage flow field around the zones, but the resulting change was not apparent to the global seepage flow field, location of the seepage face, or pore pressure gradients. The lack of change was attributed to the particularly shallow depth of the zones relative to the deeper confining layers. Changes in pore pressure caused by differences in root zone hydraulic conductivity of less than an order of magnitude were small, especially if 3D geometries were considered. However, large local increases in seepage velocity occurred when the root system was assumed to cause large increases in hydraulic conductivity. In general, the effect of a single tree in a 3D seepage flow on levee performance was smaller than the effect in a 2D flow field.

The effects of roots on soil strength were varied across several orders of magnitude, and a small increase in the Fs against slope instability was seen for a root system located at the toe when the effect of the roots was represented as significantly strengthened soil. On the other hand, if the root-soil system had significantly reduced permeability without significantly increased strength, the Fs was reduced because of the higher pore pressure. Corcoran et al. (2011) presented their findings as research results (a parametric analysis using hypothetical material properties). They recommended more research before application to actual field problems, because "without more detailed characterization of the actual material properties (hydraulic and structural) of the root-soil system, it is difficult to make precise conclusions." They also noted the need for a process model to properly assess internal erosion risk to higher seepage velocities.

10.4.2 Others

Additional 3D simulation of plant effects on slope stability using a finite element model has been described by Mao et al. (2014), who considered the effects of removing (harvesting) trees on the stability of forested slopes based on computer modeling (no field data). Although important differences exist between the cases they considered and levees, the methods used and some of the findings are relevant. They simulated the stability of bare-soil slopes, those with isolated patches of trees, and those with gaps cut into an otherwise homogeneous forest. Their model did not consider the effects of loading from wind forces on trees, the weight of trees, or hydrologic effects of roots (e.g., facilitating seepage or matric suction). Further, they did not consider the effects of large roots (greater than 10 mm) as reinforcing members, and root effects were limited to those created by adding "apparent cohesion" to soil properties. The factor normally used to convert root density and tensile strength to apparent cohesion (1.2) per the work of Wu et al. (1979) was reduced to 0.5 to account for the overestimation documented by Thomas and Pollen-Bankhead (2010).

Mao et al. (2014) found that root architecture (principally rooting depth) was a key factor, with the greatest increases in Fs caused by deep roots. In accord with many others, they found that trees at the toe of the slope had the greatest positive effects on stability. Deep roots (trees with taproots) increased Fs by about 25%, which was critical for the steeper slopes (35°) that were considered. Simulation of slopes with patches of trees showed uniform sizes and spacing created zones of weakness unless the patches were very close to one another, so staggered patterns with variable dimensions were recommended.

10.5 Data Gaps

Information on subsurface architecture of trees and soil modification by trees is more readily available now than 5–10 years ago, but is still limited to a few combinations of tree species and geotechnical, hydraulic, and hydrologic situations. Prototype data on slope stability, either with or without vegetative effects, are rare. No documentation of the systematic effects of trees on the hydraulic conductivity of levee soils has been produced. As noted in Chapter 9, "Effects of Trees on Seepage and Piping in Levees," predictions of pipe formation and enlargement are at or beyond the present state of the art. Process models of pipe formation, growth, and filling are needed. Also, slope-stability models that accurately represent forces from wind loading of trees on the slope and predict tree windthrow are needed. Currently, 3D software is available that reproduces basic physics in high temporal and spatial resolution; these tools need to be adapted to a practical level of abstraction for levee management and design.[19] Detrimental impacts of trees on slope stability identified by Simon and Bankhead (2012) include windthrow, surcharge on slopes caused by the weight of the vegetation, and enhanced infiltration from local increases in soil surface permeability. These processes are not captured in the BSTEM model. Also, some have noted that root reinforcement of soils may decline with exposure to flow if inundation periods are long and soils become fully saturated; this effect is not considered in any of the models reviewed herein.

10.6 Points of Scientific Debate

Early efforts to simulate effects of vegetation on levee slope stability (Shields and Gray 1992, Pollen and Shields 2007) were simplified. Neither study considered additional surcharge on levee slopes caused by the weight of woody vegetation or wind loads on vegetation, which is of limited importance (Norris and Greenwood 2006). Also note that increasing root contribution to soil cohesion with tree age (Table 10-1) differs from the findings of others who assessed strength of soil cores from tree plantations of different ages (Genet et al. 2006, 2008). Tests of fiber/root-

[19] Research models are typically formulated for a limited number of highly specialized users and often require large amounts of highly detailed input to describe the spatial and temporal variation in model boundaries and properties. These models are useful for deepening the understanding of a certain type of system but are not useful for widespread application to real-world problems by practicing engineers and scientists rather than research personnel. Application models typically feature thorough documentation; powerful user interfaces; default values for key inputs or menus to assist selection of key inputs; and simplified or abstracted expressions that capture only the essential temporal and spatial variation in system properties, both in input and output.

reinforced sands have shown that at equal RARs, the sands reinforced with finer (smaller diameter) fibers tend to be stronger than sands reinforced with larger diameter fibers because their total circumferential area is greater; thus, the finer fibers have a greater pullout resistance (Gray and Barker 2004).

The use of algorithms known as fiber bundle models, or FBMs, by Pollen and Shields (2007) and as described in Chapter 4 above represents a major improvement over earlier approaches (e.g., Shields and Gray 1992). Representing the contribution of roots to slope stability by simply increasing soil cohesion (the macro approach) neglects the role of large roots that cross failure planes and act as structural reinforcements, which requires a soil-vegetation interaction model such as an FBM. The FBM accentuates the importance of root architecture and tree location relative to the failure plane to the impact of woody vegetation on slope stability (Thomas and Pollen-Bankhead 2010).

As noted above, analyses by Corcoran et al. (2011) using the UTEXAS4 model were limited to failure arcs deeper than the root zone. This rendered root reinforcement irrelevant to the slope stability analysis, although root reinforcement is often a key factor in stabilizing sandy soils against shallow failures (Shields and Gray 1992, Pollen-Bankhead et al. 2009). Furthermore, the following specific aspects of the Corcoran et al. (2011) 2D slope stability models have been criticized (Harder 2012d):

- The strength/reinforcement benefits of tree roots were underestimated.
- The weight and wind loadings induced by large trees were greatly exaggerated because of the assumptions made for 3D effects.

Professional opinions differ on how best to represent 3D conditions in a 2D model. According to Harder (2012c), abstraction of 3D field conditions to 2D models can lead to discounting the positive effects of roots on slope stability and greatly exaggerating apparent loads on the slope from the weight of trees and wind loads on the aboveground portions of the trees. There seems to be no general consensus regarding the limits of 2D models to simulate effects of trees on levee slope stability. When are 2D models adequate and when are full 3D simulations required? What is the best way to convert 3D features (trees and their roots) to 2D models? Furthermore, existing approaches for simulating the effect of wind loads on trees on slope stability are less than satisfactory.

10.7 Potential Implications for Levee Vegetation Management

Numerous site-specific variables come into play when computing the exact effect of a given tree or pattern of tree growth on the slope Fs. Effects of wind loadings on trees growing on slopes are not well understood, and these loads are poorly represented in existing models. Available analyses indicate that the magnitude of the effects of trees on levee slope Fs varies widely with site conditions (e.g., levee geometry, soil properties, hydraulic loading, vegetation density, root architecture, spatial distribution of vegetation, tree health). However, there is strong consensus

that woody vegetation significantly improves levee slope stability with respect to shallow failure planes. Studies reviewed here indicate that trees increase slope stability in a positive fashion except under the most unusual conditions. For example, some computations indicate that very high winds acting on a tree at the top of a levee slope might decrease Fs, but the consensus also indicates that the models do a poor job of simulating the transfer of wind loading on the tree crown to the underlying soil.

An association between clear-cutting of forested hillslopes and slope failures has been widely noted, so any large-scale tree removals from levees would need to be completed quite carefully to avoid detrimental effects. U.S. federal policy requires removal of all roots with a diameter larger than 0.5 in when trees are removed from levees (USACE 2014), which would presumably eliminate risks associated with changes in infiltration and seepage caused by decaying root masses. However, implementation of such a policy incurs considerable risk and difficulty because of the extreme length range of some tree roots (Buer et al. 2012).

11 Risk Analysis and Levee Vegetation

Abstract
Risk and uncertainty analyses are increasingly applied to water resources management. Scarce resources may be efficiently allocated if risk reduction is a key priority. Risk analyses for levee systems may be based on some combination of analytical models, expert opinion, or experience in the form of datasets. Several examples exist of risk analyses for levee projects, but few incorporate effects of vegetation, and those that do use very rudimentary approaches. One German study used Monte Carlo analysis to predict levee breach frequencies from overtopping, and the effect of vegetation on failure probability was incorporated by including three values of "turf quality." Another study evaluated levee failure probability for several Sacramento-area levees. Expert elicitation was used to evaluate the relative probability of factors that are difficult to determine analytically, including vegetation and animal burrows. Vegetation effects on total composite failure probability ranged from less than 1% to 3%. Review of a large database of California levee performance records shows no documented influence of levee vegetation on any known breaches and that vegetation had either a documented or perceived influence on levee performance in only 16 of 7,424 records.

11.1 Risk Analysis

Risk is usually interpreted as the total probability of a defined failure criterion (e.g., levee breach and consequent flooding) within a given interval of time (usually a year) multiplied by the expected consequence, which is numerically described in terms of either dollars or lives lost.[20] Using this definition, risk has the units of dollars per year or lives per year. However, various definitions of risk are encountered in the literature, which engenders confusion (McAnally et al. 2013). USACE guidance documents define risk as the "probability and severity of loss linked to hazards" (USACE 2006, McAnally et al. 2013), while Mays (2011) defines risk as the probability of failure and reliability as the complement of risk or the probability of nonfailure. Lee and Mays (1986) define risk as the probability that the natural flood will exceed the levee capacity. Reliability is defined as the difference between 1 and the probability of failure (USACE 1995a). When defined as failure probability times consequence, and consequence is quantified in terms of dollars, the cost effectiveness of risk-reducing measures may be readily assessed or at least compared (e.g., Suddeth et al. 2010). In the case of levee vegetation, the costs of tree removals or the dollar values of environmental effects of tree removals could be weighed against the dollar value of risk reduction.

The total probability of a defined failure is computed as the probability of one or more events, multiplied by the likelihood of failure if those events come to pass. In the context of risk analysis for flood-control levees, examples of events are high stages, discharges, or certain climatic events. In some cases, the passage of time (a set number of years) might constitute an event if the

[20] Seed (2012) notes that in wake of Hurricane Katrina, USACE is moving toward prioritizing flood-control risks measured in terms of lives rather than dollars.

failure mode of interest is a continuous process such as settlement or cracking (Seed et al. 2012). Total (or composite) risk for a given structure or project that is subject to *m* failure modes and *n* events is computed as follows (Seed et al. 2012, USACE 2006):

$$Risk = \sum_{j=1}^{m} \sum_{k=1}^{n} P[event_k]\, P\left[\frac{failure_j}{event_k}\right] [consequences] \tag{8}$$

where $P\left[\frac{failure}{event}\right]$ indicates the probability of a specific type of failure caused by a given event. Note that the summation extends over all events and all failure modes. Very frequent events, say those that occur twice a year (*P[event]* = 2), may be ignored if they have a very low probability of associated failure ($P\left[\frac{failure}{event}\right] \sim 0$), because 2 x 0 = 0. Similarly, extremely rare events may be excluded even if the probability of failure for that event is high. But note that the equation above does require summation of all types of failures across all events.

The sum of the products of the first two factors in the equation above (just omitting consequences from the equation) yields the mean annual failure rate. For example, McAnally et al. (2013) point out the elevated mean annual failure rates computed for California's Delta levees: 0.006 for the Sacramento Pocket area, 0.07 for the Sargent Barnhart Tract, and 0.5 for an area of the Suisun Marsh. The reciprocal of these values gives the mean failure frequency in years. A highly simplified hypothetical calculation using the above equation is presented in Table 11-1.[21]

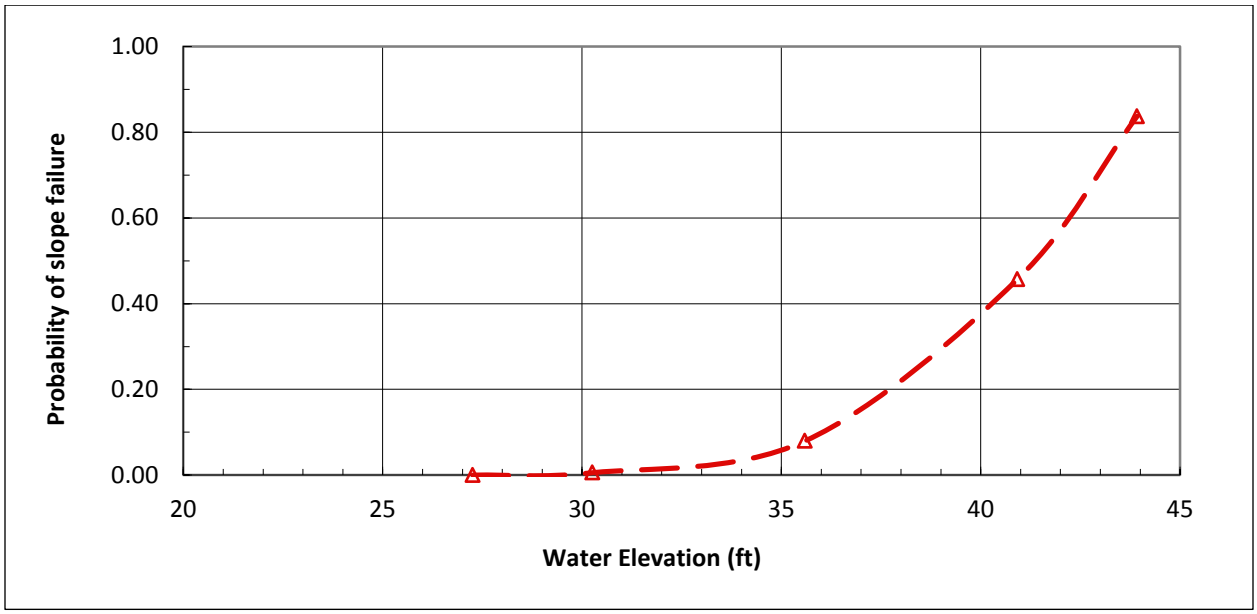
Table 11-1. Computation of Risk Using Equation 8 for a Hypothetical Levee Project

Event	Failure Mode	Event Probability (per year)	Probability of Failure	Mean Failure Frequency (years)	Consequences (10^6 $)	Risk ($)
100-year flood	Overtopping	0.01	0.2	500	50	100,000
100-year flood	Seepage-induced breach	0.01	0.05	2,000	100	50,000
100-year flood	Slope instability and associated breach	0.01	0.05	2,000	100	50,000
50-year flood	Overtopping	0.02	0.001	50,000	25	500
50-year flood	Seepage-induced breach	0.02	0.025	1,000	75	37,500
50-year flood	Slope instability and associated breach	0.02	0.01	5,000	75	15,000
Total annual risk						253,000

[21] Event probability is the reciprocal of the return interval; for example, if the return interval is once every 100 years, the event probability is 1/100 or 0.01. The probability of failure is the probability that a given failure mode will be observed if the event occurs. For example, for this location, the levee has a 20% chance of experiencing some type of overtopping in the 100-year flood. The probability of overtopping is not simply 1 or 0 because of uncertainties surrounding flood stages, levee settlement, and wave heights. However, the overtopping failure envisioned here is gradual and does not lead to development of a full breach, so the consequences are less than those for the other two modes, which do involve a full breach.

One way that the results of a probability of failure analysis can be summarized is through a fragility curve, which is a plot of the probability of failure ($P\left[\frac{failure}{event}\right]$) versus a quantitative measure of the loading event. Loading can be a flood height, discharge, duration, or return interval (Vorogushyn et al. 2009). An example of a fragility curve for a levee considering only the slope stability failure mode is provided in Figure 11-1 below.

A fragility curve (such as the one in Figure 11-1) may be used in risk analysis if there is adequate supporting hydrologic and hydraulic information. The flow frequency curve may be used to develop a probability curve for river stage, given appropriate hydraulic information to develop a reverse rating curve. A stage-probability relationship may then be combined with Figure 11-1 to obtain the annual probability of slope stability failure. If data are available to quantify consequences of failure, risk may be computed using Equation 8.



Source: Perlea and Ketchum 2011

Figure 11-1. Example Slope Stability Fragility Curve

The quantities needed to compute risk using Equation 8 must be estimated or computed from imperfect or incomplete models or data. Models may be used for quantities that may be computed analytically like slope stability or seepage, while the probability of failure imposed by other factors such as rodent activities, penetrations, or vegetation is beyond the present state of the art for general analytical computation. Nonanalytical variables or parameters may be subjectively determined from professional judgment or expert opinion (Serre et al. 2008). A procedure known as "expert elicitation" is sometimes used to reduce opinions of a group of experts to a consensus estimate of $P\left[\frac{failure}{event}\right]$ for a given failure mode and event (e.g., Perlea and Ketchum 2011, Ramsbotham 2009). Standard procedures for expert elicitation have been developed (USACE 2006).

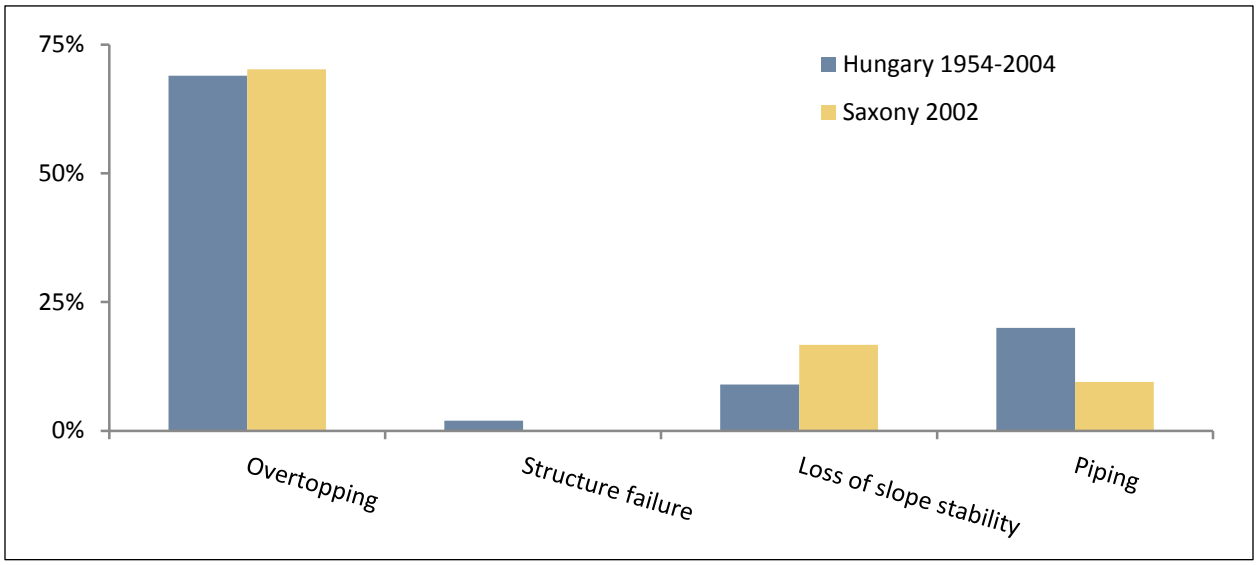
Imperfect knowledge in risk computation is referred to as "uncertainty." In the case of water resources, uncertainty has been classified as (1) hydrologic, (2) hydraulic (Lee and Mays 1986), (3) structural, and (4) economic uncertainty (Mays 2011). Others have classified uncertainty as aleatory (because of inherent randomness of a property or a process) and epistemic (because of incomplete knowledge of the system). A "first-order analysis" of uncertainty is based on examining the effect of varying input parameters used in computing the right hand of Equation 8, employing known or assumed probability density functions and mathematical techniques for varying key inputs such as Monte Carlo analysis or Taylor Series Expansion (USACE 1995a). Each uncertainty analysis method has certain weaknesses; some workers prefer the techniques of the First-Order Second Moment (FOSM) reliability method (Ang and Cornell 1974) to other methods. The limitation of the FOSM reliability method is that it is not invariant (i.e., the solution depends on the way the Fs or safety margin equations are formulated) (Sitar 2014). FOSM has been superseded by the more robust and invariant First-Order Reliability Method (FORM), which is invariant (i.e., the solution does not depend on the form of the Fs or margin of safety equation) (Ang and Tang 1984, Sitar 2014). The results of uncertainty analysis may be used to compute the uncertainty bounds associated with risk analysis outputs and to identify the contributions of individual sources of uncertainty to the overall uncertainty (Apel et al. 2004).

11.2 Risk Analysis and Levees

Equation 8 may be used to compute risk for levees. Analysis is usually performed for a levee segment of finite length using representative data from typical cross sections or other values deemed typical (Serre et al. 2008, USACE 2010a, Perlea and Ketchum 2011). Levee failure modes have been classified as (1) flood overtopping, (2) structural failure caused by slope instability, (3) structural failure caused by seepage and piping (Vorogushyn et al. 2009), and (4) erosion resulting from waves is another failure mode for Central Valley levees (Huang et al. 2010).

Failure can be functional (levees admit enough water to the protected area to produce damage) or structural (the levee embankment collapses or is breached by erosion). One mode does not necessarily imply the other. For example, a levee may be overtopped (functional failure) but not eroded enough to experience structural failure. On the other hand, structural levee failure would imply functional failure unless the structural failure was only partial (e.g., a slope failure or slump that did not compromise the ability of the levee to hold water) or a structural failure that occurred in the absence of hydraulic loading. Therefore, the failure definition must be established from the beginning for any risk analysis. Unless otherwise stated, "failure" as used herein implies functional failure. Although risk analysis includes both failure probability and consequences, the text below focuses on failure probability because the presence or absence of vegetation on or adjacent to levees will have little impact on the economic consequences of a levee failure.

Distribution of observed failures among failure categories has been presented by Vorogushyn et al. (2009) for two subsets of European levees (Figure 11-2). In reality, levee failures may be complex combinations of failure modes (Vorogushyn et al. 2009, Seed et al. 2012), and



Source: Data from Vorogushyn et al. 2009.

Figure 11-2. Distribution of Observed Levee Breaches among Four Major Failure Modes for Levees in Hungary 1954–2004 and for Levees in Saxony (Germany) during the August 2002 Elbe River Flood

combinations are sometimes analyzed through "fault trees" or failure mode and effect analysis (Serre et al. 2008).

Given a set of invariant consequences and flood event probabilities (the first and third factors of the right-hand side of Equation 8), the effects of levee vegetation on risk may be included in the risk analysis by modifying factors that control the magnitude of $P\left[\frac{failure}{event}\right]$. For example, placing riprap erosion protection on the waterside slope of a levee subject to failure driven by surficial erosion would reduce $P\left[\frac{failure}{event}\right]$. The effect of vegetation growing on or adjacent to a levee might be quantified by modifying the value of $P\left[\frac{failure}{event}\right]$. Presumably $P\left[\frac{failure}{event}\right]$ would be reduced by vegetation that increases levee slope stability, but increased if vegetation-induced through-seepage were severe enough to compromise levee stability.

Salah-Mars et al. (2008) present an extensive risk analysis for levees in California's Delta that assesses the probability of failure caused by seismic events or high water, and "sunny day" failures caused by slope instability and seepage. This study is part of a program known as the Delta Risk Management Strategy (DRMS). The probability of levee failure during the period 2003–2030 is extreme, with the probability of flooding of 10 or more Delta islands from seismic events estimated to be about 70% and the probability of flooding of 10 or more levee-protected Delta islands from a high-water event to be about 70%. The DRMS study did not attempt to explicitly account for the contribution of woody vegetation or burrowing mammals to the total probability of levee failure.

11.3 Levee Failure Probability Analysis and Vegetation

Apel et al. (2004) used Monte Carlo analysis to predict levee breach frequencies for the Rhine River downstream of Cologne, Germany. Breaching caused by overtopping was the only failure mode considered, and the effect of vegetation on failure probability was incorporated by including three values of "turf quality" that controlled the overflow depth and duration required for breach development. In an example case, variation of the turf quality from the lowest to the highest value increased the levee breach return interval from 550 years to 650 years.

Perlea and Ketchum (2011) developed a spreadsheet for evaluating levee failure probability and applied it to several Sacramento-area levees. Expert elicitation was used to evaluate the relative probability of factors that are difficult to determine analytically: failure caused by vegetation, animal burrows, encroachments, and utilities. Fragility curves were generated for specific levee segments and each of several analytically determined failure modes, as well as four modes assessed by judgment. A failure-probability computation presented for an example levee segment (Natomas Basin, Sacramento River east bank levee) found the total failure probability from nonanalytical factors for river stage at the levee crest to be 25% and for vegetation to be 3%. Similar analyses for a case study that focused on a 1,000-ft-long segment of West Sacramento river levee produced fragility curves for combined probability of failure (composite of all failure modes) as shown in Table 11-2. Vegetation increased the composite failure probability by less than 1% (USACE 2011).

Table 11-2. Combined Probability of Failure for Cases With and Without Existing Vegetation on Levee—Case Study, West Sacramento General Reevaluation Report, Sacramento River, Sacramento River South Reach 2 Station 264+00

Water Surface Elevation (ft)	Combined P(f) with Vegetation	Combined P(f) without Vegetation	Delta P(f)
20	0.0000	0.0000	0.0000
31	0.0452	0.0452	0.0000
35	0.2387	0.2310	0.0077
39	0.5214	0.5116	0.0098
41	0.7163	0.7075	0.0088

Source: USACE 2011
Notes: ft = feet; P(f) = failure probability

Ongoing work by Sitar at the University of California, Berkeley (Sitar 2014) seeks to answer the question:

> "What is the relative (or conditional) probability of failure due to the retention of existing vegetation, as compared to general failure modes such as seepage, underseepage, slope instability, erosion, or overtopping, and as compared to known risk factors such as encroachments, penetrations, sub-standard levee geometry, and animal burrows? How does vegetation change the probability of failure posed by these failure modes as influenced by such risk factors?" (CLVRP 2011)

The focus of the study is to quantify the incremental probability of levee failure from the effects of vegetation for the selected case study levees. Building upon the work of Perlea and Ketchum (2011), who incorporated the overall influence of vegetation and animal burrowing as factors in modeling, woody vegetation will be incorporated into the probability aspect of the risk assessment methodology by rationally dividing each general failure mode into risk factor subcategories based on important characteristics and overall effect on levee stability.

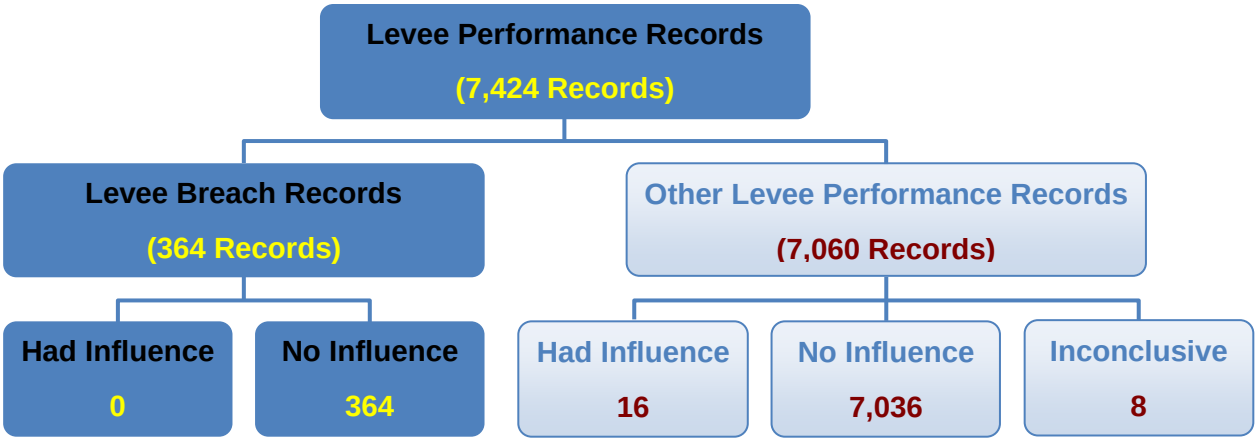
This study will use the First-Order Reliability Method, or FORM, described in Section 11.1 and will incorporate knowledge about potential interactions of levee vegetation and other failure modes through expert elicitation. The expert opinion elicitation panel will be formed and tasked to (1) assess the probabilistic quantities required for woody vegetation and animal burrow subcategories that cannot be determined analytically; and (2) assess the quantitative influence of woody vegetation and animal burrow subcategories on other potential failure modes that are evaluated analytically and judgmentally.

The primary outcome of the study is a quantification of the change in probability of failure correlated with vegetation as a risk factor.

A second outcome will be the identification of the relative impact of vegetation on failure probability in comparison to other risk factors (e.g., substandard levee geometry or animal burrows). The study is scheduled for completion in early 2017.

Research has shown that the effect of trees growing on levees on total failure probability depends on factors such as tree location on the levee, tree size, species, and condition, and such complexity might be factored into failure analyses. As noted above, the values for the three factors included in Equation 8 may be based on analytical models, expert opinion, or experience in the form of datasets. One extensive study of levee performance records was compiled under the DWR Levee Evaluation Program (Kabir and Bean 2011, Punyamurthula and Millet 2012, Punyamurthula and Musto 2014). A large dataset was compiled that contained reports, databases, interviews with local agencies and experts, historic data on levee performance, and site reconnaissance records. Using a process described by Kabir and Bean (2011), these documents were placed in a searchable database and georeferenced. More than 7,424 levee performance records were identified from the database. Each of these levee performance records were further reviewed based on breach (approximately 5%) or nonbreach (approximately 95%) performance outcome. Records were then examined for recorded evidence of vegetation recognition or perceived influence on levee performance (Figure 11-3). Of these, documentation in the data records pertaining to breach outcomes showed no indication that vegetation was perceived to have had an influence on levee breaches. With respect to other performance outcomes, only 16 records indicated vegetation with documented influence or perceived influence on levee performance.

An additional step in a levee failure probability analysis that includes vegetal factors might consider failure modes affected by removal of existing trees rather than comparing scenarios with and without trees, or with and without certain trees. Risk reductions might be achieved by removing unsound individuals (SAFCA 2009). On the other hand, Gray (2009b) has pointed out



Source: Punyamurthula and Musto 2014

Figure 11-3. Distribution of Points of Interest from Levee Performance Database

that tree removal typically leaves roots in the levee soil, which may create preferential seepage paths as roots decay (Figure 11-4). Furthermore, backfilling holes created by rootball removal is bound to create a discontinuity in embankment soil properties that may also facilitate seepage. Techniques for removing trees from levees used in the Northwest were described by Buer et al. (2012).

Reid (2005) and Seed et al. (2012) point to DRMS-computed probabilities of failure of Delta levees from seismic events as far greater than for failures caused by vegetation-related processes. Probabilities of seismic-related failure for levees surrounding low-lying islands approach 100% for time frames approaching a century (Suddeth et al. 2010). No suggestions indicating that vegetation (trees) affect the risk of seismic-related levee failure were found as part of this synthesis effort, and no investigations of the impacts of vegetation on seismic-related failure of Delta levees were found.

11.4 Data Gaps

A rigorous risk analysis that treats vegetation (trees) within the federal regulatory vegetation-free zone as a separable risk factor (i.e., not lumped with other factors) is needed to demonstrate a methodology for such analyses on a project- or region-specific basis.

11.5 Points of Scientific Debate

Available resources may be efficiently allocated by prioritizing expenditures for maximum flood risk reduction if science and information permit accurate risk quantification (referred to as a “risk-prioritized” or “worst-first” strategy). The effects of levee vegetation on the probability of failure appear to be small relative to those from other sources. However, few attempts have been made to

Source: Gray 2009b

Trees on this levee were cut down and removed by local drainage district. These roots will decay, perhaps creating zones of weakness and potential seepage paths.

Figure 11-4. Residual Roots Protruding from Earthen Levee in Portland, Oregon

quantify the effects of levee vegetation in a comparative risk analysis, so there remains controversy about the magnitude and significance of vegetation effects, including how vegetation may contribute to other levee failure modes in complex ways. Expert elicitation is one method for incorporating vegetation effects into the risk analysis. While methods for expert elicitation are standardized, expert elicitation has rarely been applied to quantifying vegetation impacts for use in risk equations, so the range of uncertainty in initial attempts may be a subject of debate.

11.6 Potential Implications for Levee Vegetation Management

Risk and uncertainty analyses are powerful tools for efficient water resources management when properly used. Incorporation of factors related to the presence or absence of woody vegetation on and adjacent to levees into risk analyses is at a very primitive state at present, and few examples exist. However, those that do exist estimate the effects of vegetation on total failure probability to be extremely small. The effects of removing legacy vegetation on levee failure risk profiles have not been quantified.

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12 Woody Vegetation on Levees and Flood Fighting

Abstract
Flood-fighting activities require that levee embankments be intensively monitored for signs of leakage, overtopping, erosion, or other forms of distress. When problems are imminent, personnel, material, and equipment must be rapidly deployed to provide temporary erosion protection, control seepage, and sometimes raise levees or build temporary flood protection structures. Some policies regarding clearing vegetation for flood fighting are based on a conservative approach to ensuring unrestricted levee access and visibility. Evidence regarding adverse and beneficial effects of woody vegetation on flood-fighting activities is extremely limited.

12.1 Flood-Fighting Activities

Flood fighting refers to operation and maintenance activities that occur during high-water events to prevent levee overtopping or levee failure. Flood fighting includes a wide range of activities that require access to levee embankments and adjacent areas for personnel, materials, and equipment such as four-wheel-drive vehicles and even larger equipment such as bulldozers or helicopters (USACE 2009a). Much flood-fighting activity requires the use of hand labor (Burnett 2007, Sills 2012). Flood fighting includes the following activities (Hynson et al. 1985, USACE 2010b, Burnett et al. 2012):

- Temporary erosion protection
- Diversion of erosive flows or creation of temporary spillways
- Local protection of structures, sewers, and water supplies using temporary barriers
- Debris removal
- Seepage control, including construction of sack rings (“chimneys”) to control boils on the landside and covering or filling of boil inlets on the waterside (boils may form on the landside floodplain at great distances [greater than 100 m] from the landside levee toe)
- Emergency filling of areas where sloughing or slippage has occurred

- Pumping[22]
- Sandbagging
- Construction of temporary walls on levee crests using lumber, sheeting, sandbags, earth fill, etc.
- Construction of setback levees or floodwalls when overtopping or failure is imminent

Many of these practices are illustrated in Figure 12-1 and by a video produced by DWR at http://www.youtube.com/watch?v=_J0WyO7pu3A and http://water.ca.gov/videorelease/floodpreparedness.cfm.

Besides these activities, flood fights normally include nearly continuous inspections (Sills 2012) or high-water patrols (Cunny 1987, Burnett et al. 2012). These need to be rapid (Carter and Anderson 1984) and efficient even though they often must be performed in inclement weather and in darkness.

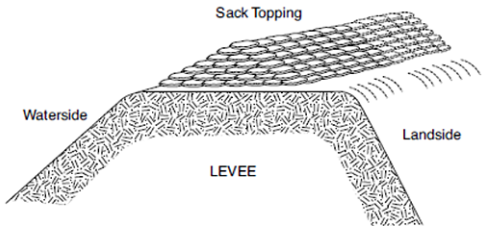
Flood-fighting practice is not taught in standard engineering curricula, so techniques and strategies are taught on the job, through short courses, and are documented in gray literature (e.g., USACE 2010b, Burnett et al. 2012). Considerable creativity is often required because of visibility and access problems related to moist soils, ponded water, boils, terrain, and vegetation (Sills 2012, List 2012).

12.2 Woody Vegetation and Flood Fighting

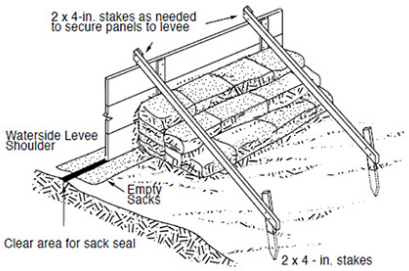
Current U.S. national policy documents stress the need to maintain vegetation-free zones (VFZs) or corridors on and adjacent to levees to prevent hindrance of flood-fighting activities (e.g., USACE 2009a):

> a. The VFZ is a three-dimensional corridor surrounding all levees, floodwalls, embankment dams, and critical appurtenant structures in all flood damage reduction systems. The VFZ applies to all vegetation except grass. Grass species are permitted, as described in Paragraph 4-8, for the purpose of erosion control.
>
> b. The primary purpose of the vegetation-free zone is to provide a reliable corridor of access to, and along, levees, floodwalls, embankment dams, and appurtenant structures. This corridor must be free of obstructions to assure adequate access by personnel and equipment for surveillance, inspection, maintenance, monitoring, and flood fighting. In the case of flood fighting, this access corridor must also provide the unobstructed space needed for the construction of temporary flood-control structures. Access is typically by four-wheel-drive vehicle, but for some purposes, such as

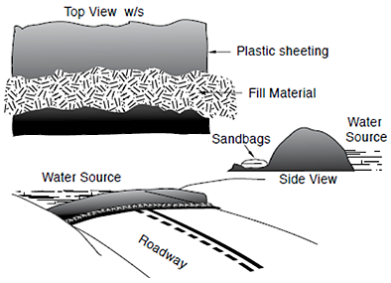
[22] Pumping is sometimes used to relieve flooding caused by collection of seepage or local runoff on the landside of levees during flood fights (USACE 2010b).



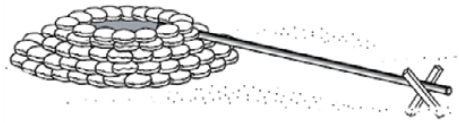
(a) Sack topping on a levee



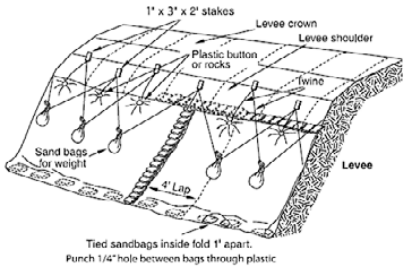
(b) Lumber and sack topping



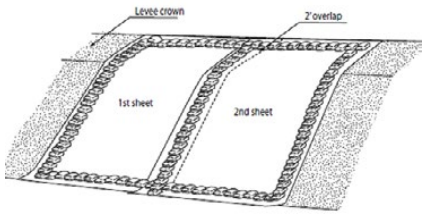
(c) Temporary levee



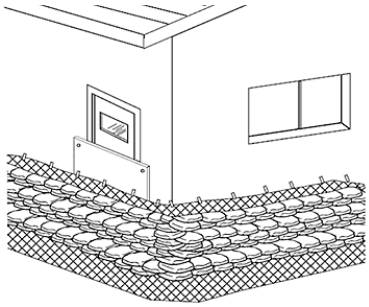
(d) Boil sack ring



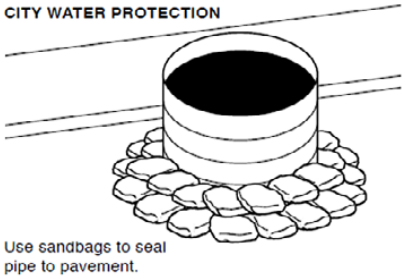
(e) Wave wash protection



(f) Emergency spillway using plastic sheeting and sandbags



(g) Structure protection (note that some agencies require freestanding sandbag protection structures, as buildings are not designed for additional loads)



(h) Water/storm drain protection

Source: Burnett et al. 2012

Figure 12-1. Typical Flood-Fighting Methods

maintenance and flood-fighting, access is required for larger equipment, such as tractors, bulldozers, dump trucks, and helicopters. Accessibility is essential to the reliability of flood damage reduction systems.

There is almost no literature dealing with the effects on flood-fighting activities of trees and shrubs growing on or near levees. Much of the content of this document is drawn from transcripts from the 2007 Levee Vegetation Symposium and the 2012 Levee Vegetation Research Symposium, both of which are available online (see cited materials in Chapter 17, "References").

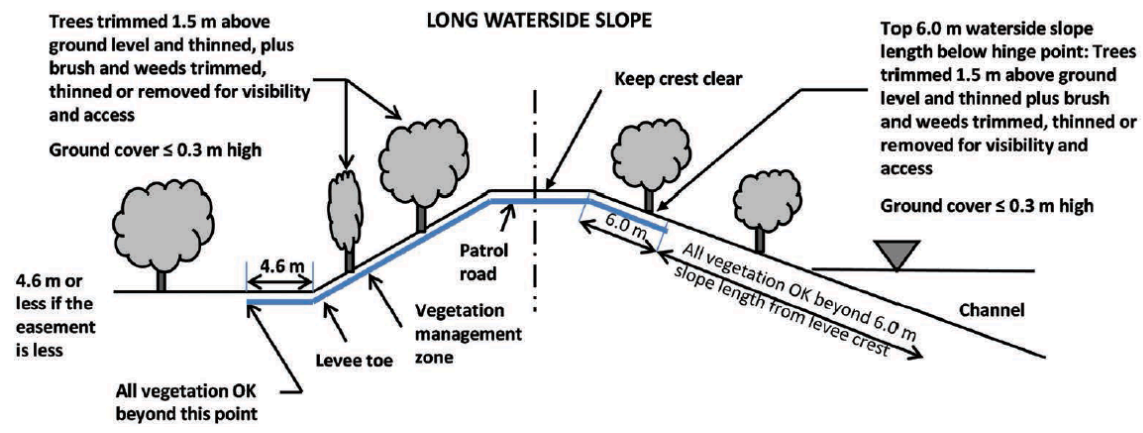
Woody vegetation can impede these activities by acting as a visual barrier, preventing access (Kleber-Lerchbaumer 2012), or complicating emergency repair activities by requiring additional tasks for vegetation removal. However, at least three engineers with long records of flood-fighting experience in different regions of the U.S. noted that they had never personally witnessed significant adverse impacts by woody vegetation on flood-fight access or flood-fighting activities in general (Burnett 2007, Sills 2012, Bean 2012).

Even levees free of tree growth may have conditions that impede visual access and require walking inspection during flood fights. Tall grass and dense growths of nonwoody species (e.g., blackberry vines) can present visual barriers similar to trees. Manmade encroachments such as fences, houses, pipelines, and other structures also block access and visibility, especially in urban areas. Sills (2012) advocated walking inspections over inspections from vehicles driving on the levee crest, and stressed the necessity of being able to see the ground. Vehicle access to the landside levee toe for inspection during floods is often not feasible because of a lack of all-weather roads. Additional information regarding inspection and levee vegetation is presented in Chapter 13.

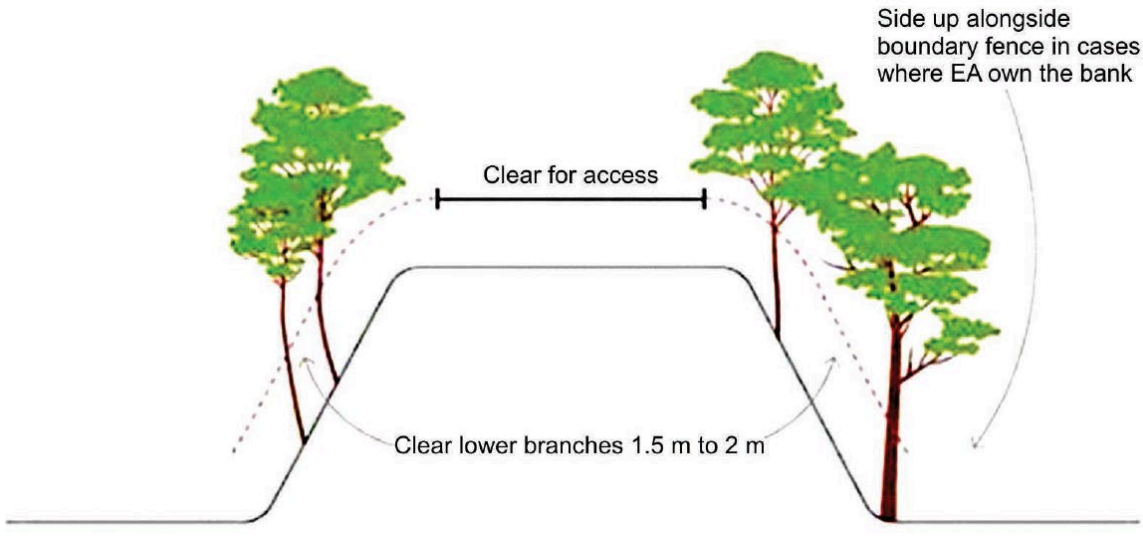
Trees near levees can aid flood fighting by serving as a source of brush for temporary structures (USACE 2010b) and by making soft, moist soils more trafficable (Sills 2012). Stands or strips of waterside trees that protrude above the water surface can indicate conditions below the surface that would otherwise be invisible (e.g., slumps or slides) (Bean 2012).

12.3 Vegetation Management for Flood-Fighting Objectives

Bean (2012) noted that regional inspection standards in force in his area (King County, Washington) allowed for 4-ft-diameter clumps of woody vegetation on 30-ft centers on nonfederal levees (USACE 1995b). Patterns such as this have been created by clearing existing thickets. The gaps between the 4-ft clumps of woody brush (e.g., young willow trees) allow for visual inspection and access. However, such clumps may concentrate erosive flows or trigger local scour. Furthermore, repeated cutting is necessary because willows resprout vigorously from the cut stems. Other workers have suggested cutting trees and shrubs on levee slopes to produce chevron-shaped patterns such as the one shown in Figure 13-1 (see Chapter 13, "Vegetation and Levee Inspection") for visibility and access. Guidance for trimming and thinning levee vegetation provided by DWR and by the Environment Agency of the United Kingdom are shown in Figure 12-2. Additional information on vegetation management to facilitate routine (not flood-fight) inspection is found in Chapter 13.



Thinning and trimming practice for urban levees in California by California Department of Water Resources (DWR 2012b).



Thinning and trimming for levees in England and Wales (Environment Agency).

Source: CIRIA 2013

Figure 12-2. Guidance for Thinning and Trimming Woody Vegetation on Levees to Facilitate Flood Fighting and Inspection

12.4 Data Gaps

There is almost no literature dealing with the effects of trees and shrubs growing on or near levees on flood-fighting activities. Objective, experimental studies would be difficult to conduct (it is not possible to schedule floods in most reaches) and of little value because of site-specific, uncontrollable variables. Interviews of key flood-fight personnel conducted shortly after the conclusion of flood fights might yield some useful data, but such interviews should be designed and analyzed by social scientists with appropriate expertise.

12.5 Points of Scientific Debate

Preserving access and visibility for flood fighting is often cited as a reason for strict limits on levee vegetation. Professional opinions differ regarding the impacts of levee vegetation on flood-fighting activities, including high-water patrolling. No studies or surveys have been done to test theories or quantify data to inform policymakers. Clearly, differences in landside land cover vary greatly from arid to humid ecoregions, and such regional differences are reflected in experiences and attitudes of flood-fighting professionals. For example, when spotting sand boils along levees, vegetation would likely present less difficulty in the Southwest than in the Midwest.

12.6 Potential Implications for Levee Vegetation Management

No research or systematic studies of current practice on this topic were found. Flood-fighting experts who participated in the 2012 Levee Vegetation Research Symposium reported that, in their experience, the presence of trees and shrubs on levee slopes or in adjacent areas did not create significant adverse impacts on flood-fighting activities.

13 Vegetation and Levee Inspection

Abstract
U.S. federal regulations require regular inspection of levees to detect flaws such as erosion, slumping, and other signs of distress. One key rationale for prohibiting trees and shrubs on and immediately adjacent to levees is their impact on visibility and accessibility for inspection. Suggestions for addressing these concerns short of tree removal include the increased use of walking inspectors and application of guidelines for cutting and trimming trees and shrubs to allow views under the canopy. No published scientific research on effects of vegetation on routine levee inspection was found. A study of burrowing mammals reported that the effort required to locate mammal burrows in levee slopes was three times greater for slopes under "dense grassland and shrubs" as opposed to "barren soil and sparse grassland."

13.1 Relevance to Levee Performance

Levees must be visually inspected for seepage, cracking, sinkholes, settlement, displacement, other signs of distress, animal burrows, holes, cracks, compromised erosion protection, and unauthorized penetrations on a regular basis and at high frequency during high-water events (33 CFR 208.10). Inspections in the U.S. are performed by local sponsors in accordance with 33 CFR 208.10 and less frequently by USACE (USACE 2015). Many inspections are performed from vehicles driven along the levee crown with personnel watching both sides, but detailed inspections conducted at 5-year intervals by USACE personnel must be completed by a multidisciplinary team "physically walking the levee alignment and associated inspection areas." Cunny (1987) describes walking inspections of the landside levee toe during high-water events to detect seepage issues.

One of the issues surrounding levee vegetation is the impact of various types of vegetative cover on the visibility of and access to the levee and adjacent areas for inspection (Gray et al. 1991, USACE 2009a). This chapter deals with routine and periodic inspection issues; inspections conducted during high water are described by Cunny (1987).

13.2 Sources of Information

Because virtually no scientific research has been completed on this topic, this synthesis is quite brief. It serves as a placeholder for future research and investigation. As noted below, the available literature deals with related issues, but not directly with the impact of trees and shrubs on the efficacy and efficiency of required levee inspections.

13.3 Walking Inspection

Hynson et al. (1985) briefly discuss the use of walking inspection as an alternative to more orthodox patrolling with moving vehicles. Walking inspectors can view the levee embankment from the toe of the slope, and can see underneath the vegetative canopy that would obscure views from the crown. Hynson et al. (1985) state:

> Research by the California Department of Water Resources indicates that inspectors can effectively detect areas needing maintenance on levees supporting tall grass for a distance 15 feet upslope from their position. Thus, one side of a levee embankment 30 feet along the slope would require two persons to inspect it, one at the toe of the levee and one at midslope.

No citation is given for the DWR research, however.

Walking inspection has been used by some California landowners (Riley 1981) and in the Portland District of USACE along levees that do not have access roads along their crowns (Hynson et al. 1985). The costs of walking inspection are likely higher because it is more labor intensive (Hynson et al. 1985). A larger number of inspectors would require training, and training techniques might be different for walking inspection. Workers in the Netherlands have proposed the use of 3D video games to train levee inspectors (Hounjet et al. 2009, Harteveld et al. 2010). Others have proposed supplementing visual inspection with sensor technology (Sips et al. 2013) or airborne synthetic aperture radar to detect surface deformations, subsidence, and seepage (Jones et al. 2012).

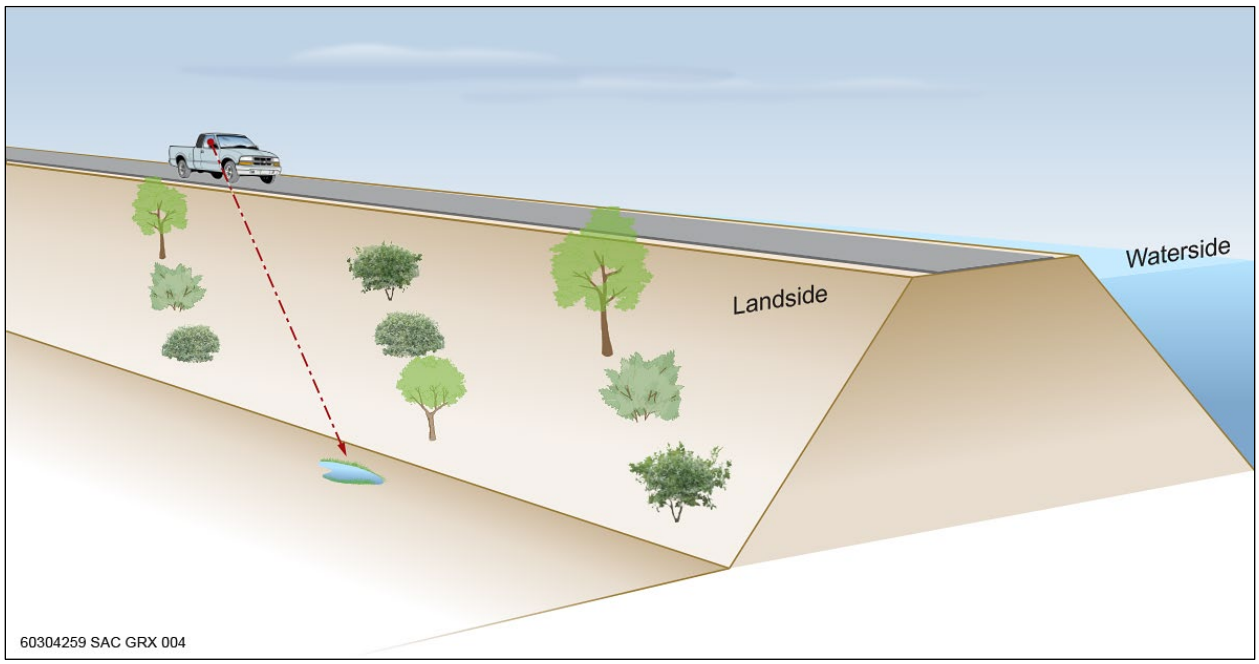
Ordenaña et al. (2012) describe the meticulous process they used to locate mammal burrows on California levees:

> We searched each segment visually for burrow entrances and counted all entrances, measured their diameters, and recorded the presence of excavated soil and runways to aid in identifying the species that excavated the burrow. Because of the possibility of detection bias due to differential visibility among habitats, we searched each segment systematically by establishing parallel, adjoining transects along the longitudinal axis of the levee, from the crown down to each toe, such that the entire surface area of the segment was covered by transects. Transects were 1.0–1.5 m wide in open habitats such as barren soil and sparse grassland where surface visibility was excellent, and 0.5 m wide in habitats such as dense grassland and shrubs where visibility was reduced. We slowly walked the center of each transect and visually searched the ground surface for burrow entrances. When dense shrubs impeded walking, we proceeded on hands and knees to ensure that we searched the entire ground surface. We manually probed clumps of dense grass or patches of leaf litter that might conceal a burrow entrance. Complete searches required up to 8 person-hours of effort per [50 m in direction of levee axis] segment.

According to this description, roughly three times as much effort (based on transect spacing) was required to locate all burrows when vegetation was “dense grassland and shrubs” as opposed to “barren soil and sparse grassland.”

13.4 Management of Vegetation for Inspection

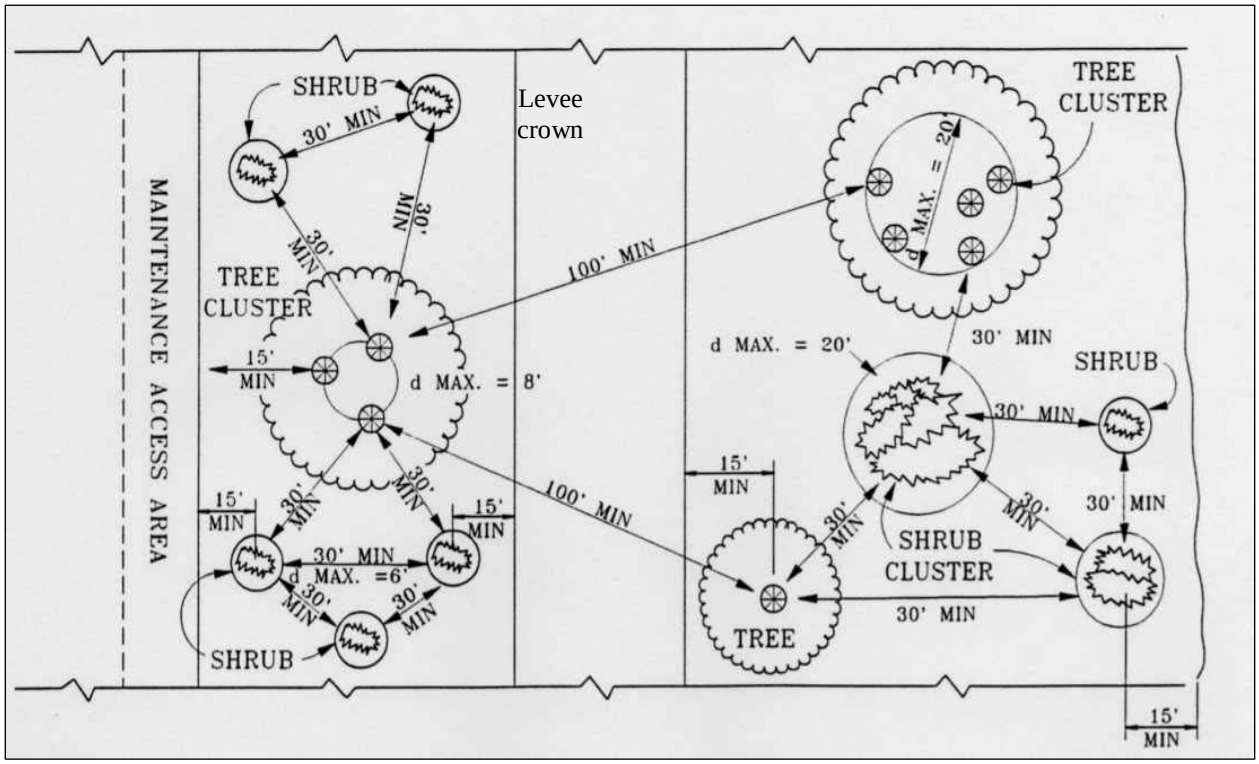
Other workers have proposed managing woody vegetation on levee slopes to facilitate inspection visibility and access (e.g., Zanetti et al. 2012). Possible approaches include (1) cleared viewing corridor, (2) cluster methods of vegetation placement, (3) selection of appropriate vegetation, and (4) pruning strategies such as thinning, coppicing, stub-cutting, pollarding, and canopy shaping (D. Gray, personal communication 2013). An example of the cleared viewing corridor approach includes cutting vegetation to create “chevron” or inverted v-shaped patterns that create open corridors so that inspectors at the crown can view segments of the slope all the way to the toe (Figure 13-1). Regional inspection standards for nonfederal levees in the Seattle District of USACE included provision for 4-ft-diameter clumps of woody vegetation on 30-ft centers (USACE 1995b).



Source: River Partners 2013, adapted by AECOM in 2015

Figure 13-1. Schematic of Use of Chevron Patterns for Woody Vegetation on Embankment Slopes to Allow Visibility for Inspections

One scheme for allowing tree clusters is illustrated in plan view in Figure 13-2. Several vegetation management techniques were recommended for the Alameda Creek Flood Control Project by Osmundson and Associates (1971) to produce a project that was inspectable but yielded valuable ecosystem services.



Source: D. Gray, personal communication 2013

Figure 13-2. Plan View of Scheme for Allowing Clusters of Trees and Shrubs on Levee Slopes to Allow Visibility and Access for Inspection

The State of California developed vegetation management guidelines for levees in 2007 (Central Valley Flood Protection Board 2009). These guidelines, DWR's Interim Levee Vegetation Inspection Criteria, specified that:

> Trees be must be trimmed up five feet above the ground (12 feet above the crown road) and thinned enough for visibility and access. Brush, weeds, or other vegetation over 12 inches high blocking visibility and access within these levee areas should be trimmed, thinned, mowed, burned, dragged, or otherwise removed in an allowed manner. These criteria apply on the entire landside slope plus a 10-foot wide easement beyond the landside toe. On the waterside, these criteria apply to vegetation on only the top 20 feet (slope length) of the levee slope.

Similar, but more recent (ca. 2012) vegetation management guidance issued by DWR is depicted in Figure 12-2.

13.5 Data Gaps

Almost no hard data are available regarding effects of varying types and spatial arrangements of levees on the accuracy and efficiency of visual inspection. Data might be obtained by well-

designed studies in which the same team of inspectors attempted to locate simulated deficiencies along levees with varying vegetative cover conditions. For example, levees with similar geometry and supporting growths of only grasses, isolated trees, dense tree and shrub cover, and woody vegetation trimmed or cut in some of the ways described in this chapter to accommodate inspection could be included. Analysis of results should include costs (economic factors) of obtaining acceptable levels of inspection accuracy on all types of studied levee vegetation regimes.

13.6 Points of Scientific Debate

It is unknown how much risk of levee failure is increased by faulty inspection, or whether woody vegetation on levee slopes actually causes inspectors to overlook critical flaws. Access and visibility are hindered by high grass, blackberry vines, ivy, untrimmed trees, fences, and other manmade encroachments. Questions remain about the efficacy of trimming and thinning trees in removing or mitigating hindrances to inspection. Further, economic comparisons between an approach featuring the use of walking inspectors working more slowly around trees and shrubs and one featuring the use of fewer inspectors working more rapidly on levees devoid of woody vegetation have not been published.

13.7 Potential Implications for Levee Vegetation Management

The effect of woody vegetation on and adjacent to levees on levee inspection will remain controversial in the absence of hard data and information. Techniques have been suggested but not yet studied to avoid or minimize vegetation impacts on inspections, such as the use of walking inspectors, well-enforced vegetation management guidelines, and the use of special sensors to detect problems and supplement visual inspection.

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14 Levee Design Features to Reduce Risk and Uncertainty Associated with Vegetation

Abstract
Trees and shrubs are often prohibited from levee embankments because of several factors, including the difficulty of quantifying their impacts on levee performance under flood loadings. Key concerns include that root penetration of the levee embankment may create preferential flow pathways, and windthrow of trees may remove enough material from the levee prism to degrade levee safety. Design features to counter these concerns include overbuilt embankments and plastic or metal root barriers inserted into the levee structure. Barriers of metal or plastic buried in the levee have also been suggested for controlling hazards associated with animal burrows. There is experience with overbuilt levee embankments, and USACE guidelines exist for overbuilt dimensions that allow for planting berms. An experimental levee designed and constructed with slope plantings of shrubby willows in Europe showed the willows reduced soil water content relative to an unvegetated levee but exhibited soil moisture levels similar to a levee under grass cover. Study of the performance of soil-cement-bentonite seepage cutoff walls retrofit into Sacramento River levees revealed that tree roots grew along, into and sometimes through the cutoff walls.

14.1 Levee Designs with Intentionally Planted Vegetation

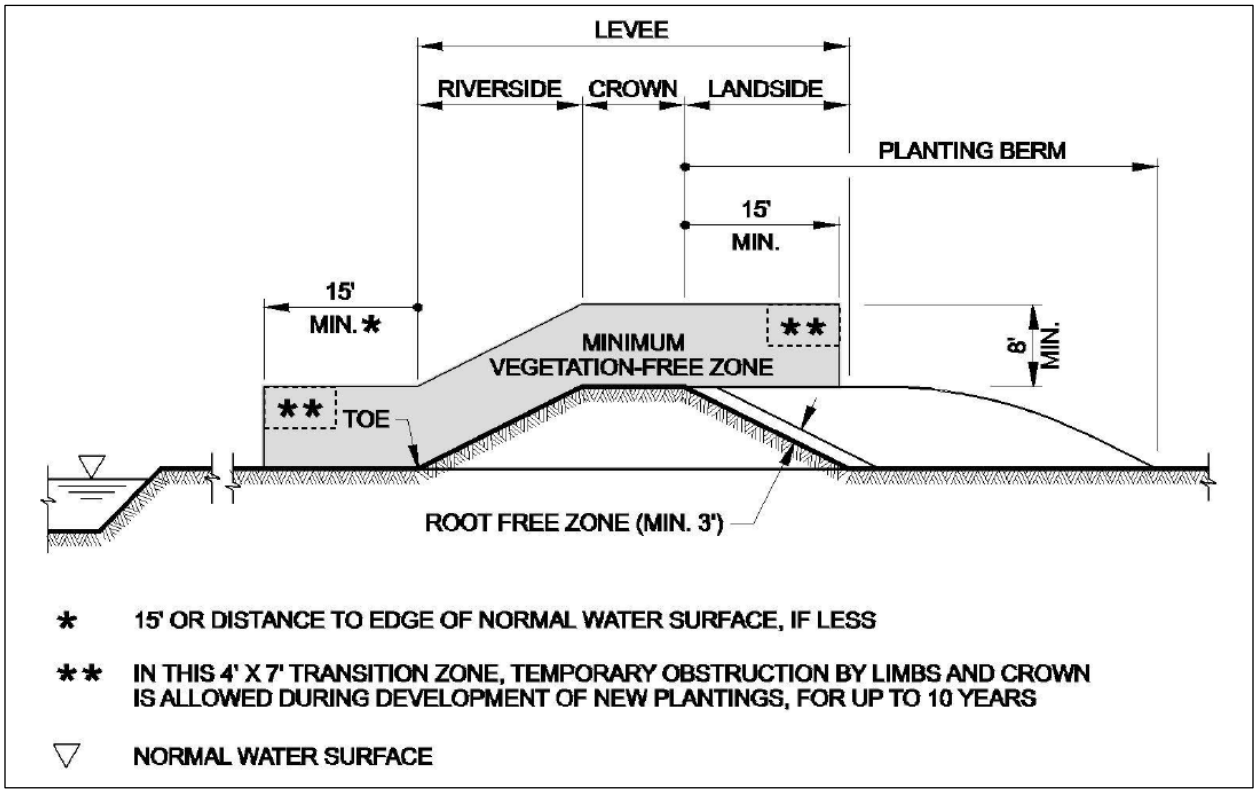
14.1.1 Planting Berms

Trees growing on or near levees exhibit various forms of root architecture in response to environmental variables and because of specific traits as described in Chapter 2, "Woody Plant Root Architecture on and around Levees." Current guidance and policy promulgated by USACE (2014a) addresses uncertainty regarding spatial and temporal root distribution. The policy allows woody vegetation on "planting berms" added to levee slopes under strict limits (Figure 14-1):

- Planting berms are limited to the landside of the levee.[23]
- Planting berms consist of earth fill in excess of the minimum section needed to satisfy stability requirements.
- The planting berm must be of sufficient depth to accommodate any proposed vegetation and preclude root penetration into the root-free zone.

[23] There are bank protection projects that USACE constructed under the Sacramento River Bank Protection Project authority along the lower American and Sacramento Rivers that included construction of waterside berms to address erosion and provide on-site mitigation. Because levees along these rivers are located on channel top banks, these berms are in fact waterside planting berms. This design approach was used extensively before the issuance of Engineering Technical Letter 1110-2-571 (T. Washburn, personal communication 2014).

- Design must include consideration of any internal drainage or seepage control system.
- No vegetation is permitted on any "overbuild" that has a system-reliability function except in planters (e.g., concrete vessels).
- Adequate access between the levee toe and the levee crown must be maintained for inspection and flood fighting. Specifically, visual access is required for inspection of the toe area and physical access is required for flood-fighting activities involving personnel and heavy equipment.



Source: USACE 2014

Figure 14-1. Definition of Root-Free Zone and Minimum Vegetation-Free Zone for Simple Levee Section with a Planting Berm

As shown in Figure 14-1, the root-free zone must be a minimum of 3 ft thick. Previous USACE guidance was similar to that described above, but levees with planting berms were referred to as "overbuilt" levees (Hynson et al. 1985, Gray et al. 1991). Several levee projects in the U.S. have featured plantings on overbuilt sections, as summarized in Table 14-1.

14.1.2 Inclusion of Plant Materials in Levee Embankment

A long-term research project in Austria is investigating the performance of earthen levees that had various biotechnical measures installed during construction in 2007 (Lammeranner et al.

Table 14-1. Selected U.S. Levee Projects with Overbuilt Sections

Project	Location	Type of Vegetation	Remarks	Source(s)
Alameda Creek	San Francisco Bay area	"No mow" zone on levee	Planted vegetation did not survive; many plants stolen by vandals	USACE 1969, Osmundson and Associates 1971, Osmundson 1980
Cedar River	Evansdale, Iowa	Landscape plantings	Promote visual diversity and landscape plantings	USACE 1970
Tenn-Tom Waterway Canal section	Northern Mississippi	Natural revegetation	Levee built with material excavated for canal	USACE 1982b; McLindon 1985
Snake River and Clearwater River	Lewiston, Idaho	Turf and trees and shrubs in containers	Levee is part of an urban parkway	Osmundson 1972, 1973

Source: Hynson et al. 1985

2007a, 2009a). The project is examining the effect of small, shrubby plants on seepage under hydraulic loading and on erosion under overtopping conditions. The objective is to develop levees with woody vegetation that provides benefits (slope stabilization, erosion protection) without the perceived disadvantages of larger trees (windthrow, creation of seepage paths, local scour around trunks). The research levees were built at prototype scale and arranged to create a rectangular basin that may be filled with water. The levee embankments comprise well-compacted (dry density = 123 pounds per cubic ft) silt-sand-gravel soil and have a fill height of 8.9 ft and a slope inclination of 2:3 (vertical:horizontal). Four types of vegetative measures were installed on discrete segments of the levee (Figure 14-2): dormant cuttings, living brush mattress (longitudinal), living brush mattress (transversal), and jute netting over seeded mulch.

Source: W. Lammeranner

Figure 14-2. Experimental Basin (left) Shortly after Construction and Planting, and (right) Showing Various Vegetation Treatments under Hydraulic Loading

The dormant cuttings and living branches were the shrubby willow *Salix purpurea L.* A mixture of grass- and herb-seeds suited to dry conditions was used for seeding of the mulch/jute netting treatment. Investigators have reported the above- and belowground growth and development of the plantings, tabulating parameters including shoot diameter, shoot length, biomass, leaf area index, rooting depth, root distribution, root diameters, and root mass. Effects of plants on seepage have also been monitored using appropriate instrumentation. Effects of willows and grasses on soil moisture were examined using tensiometers in small lysimeters. Preliminary conclusions based on 2009 and 2010 data (Lammeranner 2012) include:

- Shrubby willows grown from brush mattresses seem to be an appropriate vegetation form[24] for well-compacted levees.
- They develop a dense and near-surface root system, but with more roots at depth than grasses.
- They form a dense stand of thin and flexible stems.
- During the period of observation, the willows did not have a significant impact on seepage, as piezometers mounted within the embankments under the grassed sections and those supporting willow treatments exhibited very similar behavior when the interior basin was flooded.
- They have a significant positive impact on soil water balance, reducing soil water content relative to an unvegetated levee but similar to a levee under grass cover.

Similar conclusions may be drawn from more recent data, except that the stand of willows is becoming less dense as the plants mature (5 years old as of 2012) (W. Lammeranner, personal communication 2013). Further development is the subject of ongoing research.

14.2 Retention of Existing Vegetation

14.2.1 Overbuilt Sections

Washburn (2012) also used the term “overbuilt” in describing the design of new levees along the Sacramento River to protect the Natomas Basin. No reference was made to a “root-free zone,” but a method was developed and approved by USACE to determine how much additional material must be added to the landside of an existing levee to allow retention of existing waterside trees. The key criterion called for a distance of 10 ft running perpendicular from the 2:1 (horizontal:vertical) waterside slope of the basic levee section to the crown waterside hinge

[24] The phrase “seem to be an appropriate vegetation form” is a preliminary conclusion by Lammeranner (2012). According to Lammeranner (2012), the willows have characteristics that would make them valuable for protection against surficial erosion (dense stand of thin, flexible stems) and slope stability (positive impact on soil water balance), without unattractive properties that would make them a liability: they are not large enough to be a windthrow or local scour hazard, they do not facilitate seepage, and they do not obstruct the floodway.

point (Figure 14-3). The resulting levee structure had a crown width of 44 ft and a 3:1 (horizontal:vertical) landside slope. The 10-ft normal dimension was associated with a waterside "sacrificial zone"[25] associated with potential tree blowover and scour, and the 44-ft crown width includes the sacrificial waterside portion.

Washburn (2012) also detailed similar analyses used to evaluate existing levee sections protecting the Little Pocket and Pocket areas along the Sacramento River east bank south of the American River confluence. Here the key criteria were based on the projected maximum depths of holes created by root pits[26] from windthrown waterside trees, made deeper by scour. It was assumed that the maximum root pit depths were 3–5 ft, and standard bridge pier scour equations were used to forecast deepening based on the angle that the fallen tree made with the river current ("skew angle" in Figure 14-4). In many cases, these analyses showed that the existing levee sections were overbuilt with respect to these criteria. Washburn (2012) suggested that overbuilt section thicknesses needed to protect against potential scour of root pits of windthrown trees be evaluated in light of the joint probability (likelihood of co-occurrence) of factors that must all occur to create a hazard of levee failure: (1) tree windthrow, (2) tree skew angle to produce a given depth of scour, and (3) flood loading to promote conditions needed for levee failure.

14.2.2 Barriers

Mechanical or biological barriers may be used to prevent roots from penetrating embankments. For example, in the U.S., USACE regulatory guidance (USACE 2014a) provides that:

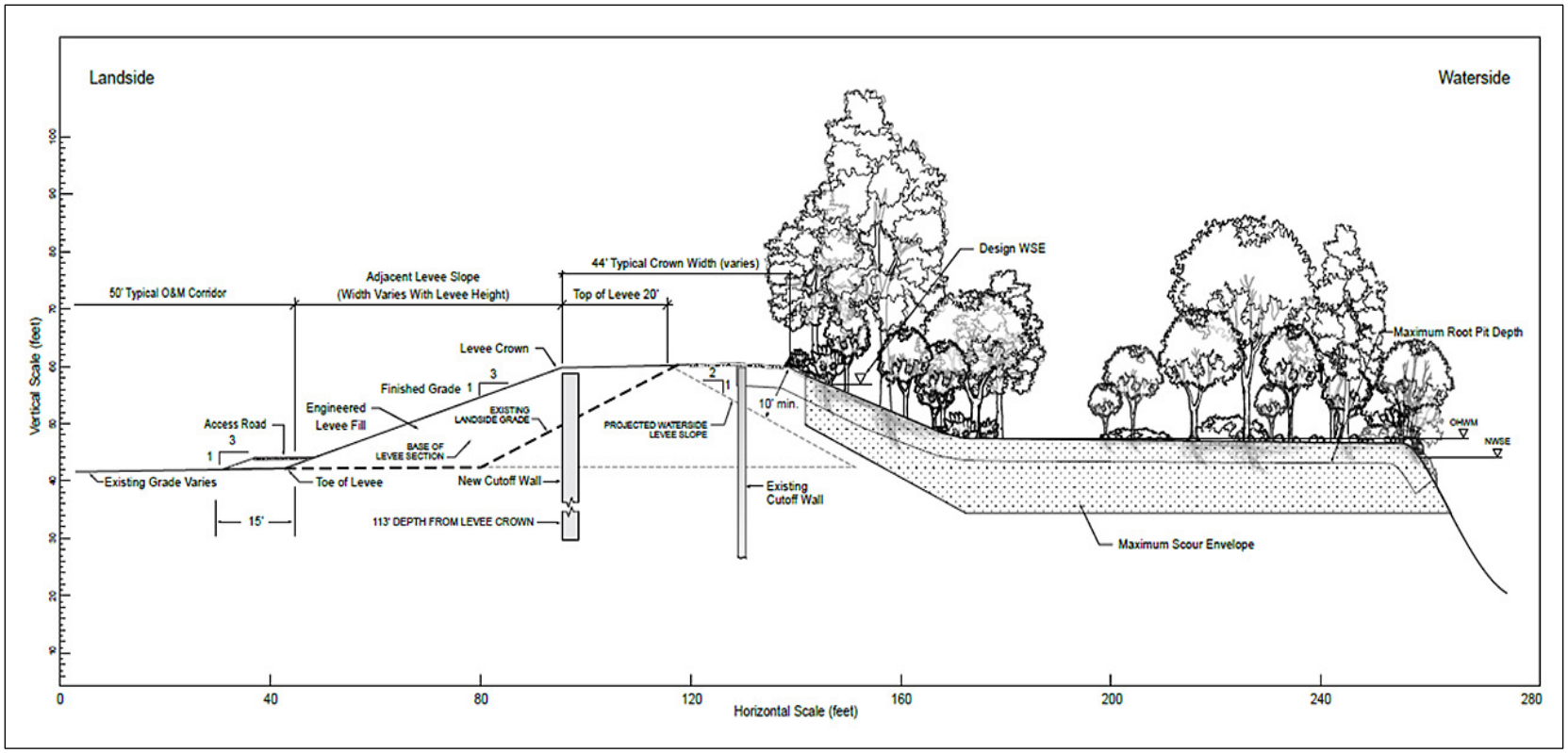
> Root barriers may be used to provide an additional measure of assurance, but they should not be a substitute for adequate distance between plantings and root-free zones. Root barriers shall not retard groundwater or seepage flow. Some root barriers include herbicides to enhance effectiveness; in every case, these shall be evaluated prior to use to assure against negative environmental impacts.

Biological root barriers are commercially available. For example, one product is a porous geotextile that slowly releases the herbicide trifluralin, which works by creating a vapor zone where roots will not grow (www.biobarrier.com/). Other products are plastic mesh or panels that provide a mechanical barrier to roots and in some cases, soil moisture (e.g., www.deeproot.com, www.centuryrootbarrier.com).

Cutoff walls are sometimes included in levees to prevent seepage. Existing levees may be retrofitted with cutoff walls using the slurry-trench method. Slurry walls may be made of mixtures of soil, cement, and bentonite. If intact, slurry walls eliminate seepage through the levee and control underseepage to the depth of the base of the wall. Even if slurry walls are compromised by cracks or by penetrations from roots, animal burrows, or other causes, they still

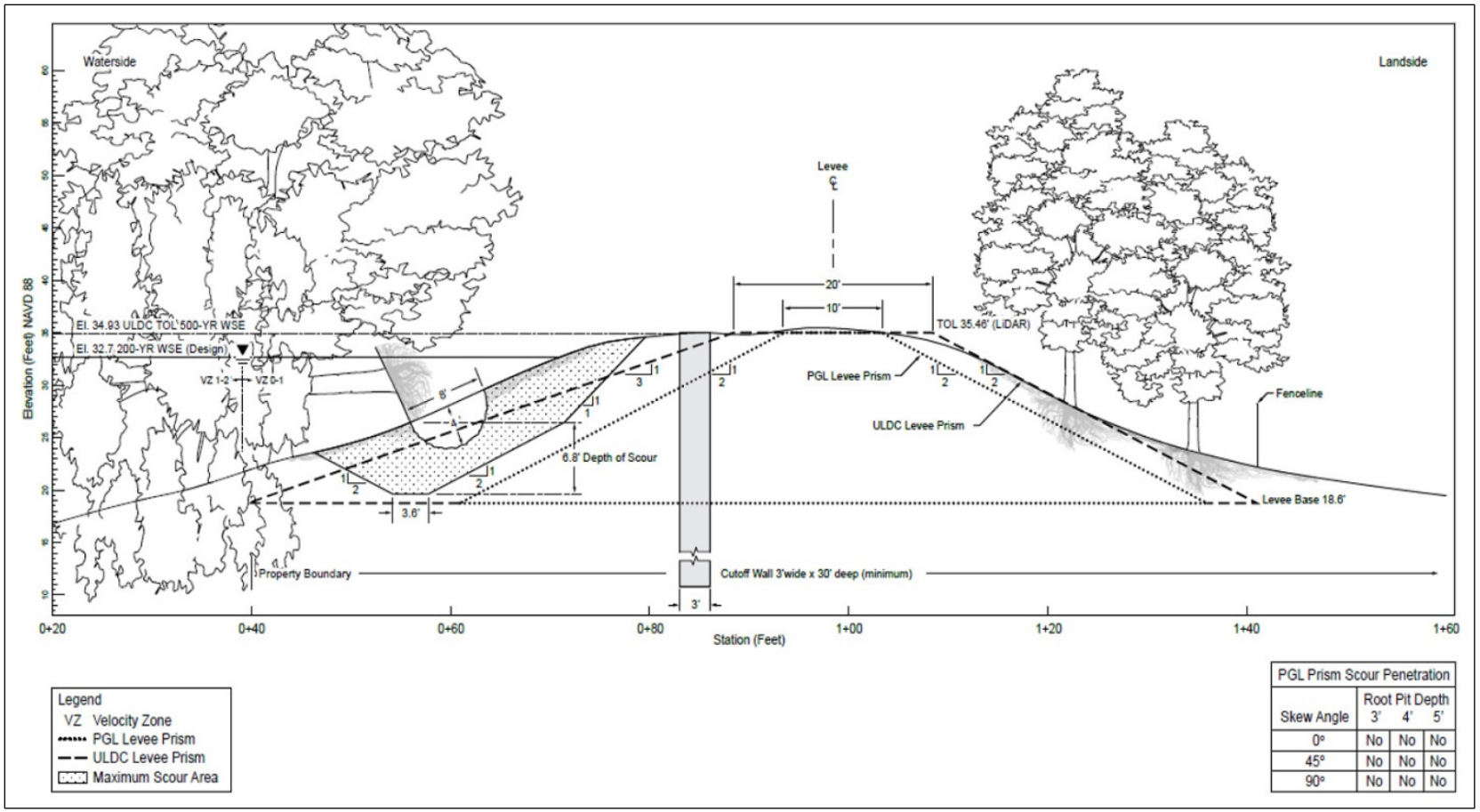
[25] "Sacrificial zone" refers to a section of levee where material (soil) could be removed (sacrificed) by treefall or erosion without degrading levee reliability because the basic levee section would not be affected.

[26] "Root pits" refer to holes left by removal of the root mass when trees are overturned by wind. See Chapter 7, "Hazards to Levees from Treefall," for more information.



Source: Adapted from Washburn 2012

Figure 14-3. Method Used to Assess the Adequacy of Natomas Levee Design



PGL Prism Scour Penetration			
Skew Angle	Root Pit Depth 3'	4'	5'
0°	No	No	No
45°	No	No	No
90°	No	No	No

Source: Adapted from Washburn 2012

Figure 14-4. Method Used to Assess Adequacy of Existing Levee, Little Pocket Area

partially protect the levee from seepage erosion (piping) because the slurry wall material is resistant to erosion itself. If hydraulic head builds up on one side of a barrier, rapid flow through small cracks may produce erosion. The situation is complex, however, as erosion of the crack enlarges it, reducing velocity and perhaps causing erosion to cease. The potential for enlargement of a crack or any type of opening in a seepage barrier is a function of three factors: the size of the opening, the hydraulic conductivity of the surrounding soil, and the resistance to erosion of the seepage barrier material (Rice and Duncan 2010).

Harder et al. (2010, 2011) and Harder (2012b) reported results of a series of careful excavations to expose 1- to 1.5-ft-thick slurry walls in sandy levees along the Sacramento River in Sacramento, California (Figure 14-5). Harder concluded that these slurry walls (which were old, low-density, high-moisture materials) were only partially effective as root barriers. Trenches were dug on levee crests parallel to soil-cement-bentonite slurry walls constructed in very old, sandy levees in 1991. The slurry wall material, sampled about 4–5 ft below the surface, proved to be low density, relatively weak, and moist. The moist unit weights were about 75–80 pcf, while dry unit weights were about 40 pcf. Water content was 80% to 90%. Two samples were tested for compressive strength and yielded 15–25 pounds per square inch. More recently constructed slurry walls comprise denser materials.

Source: L. Harder

Figure 14-5. Excavation of an 18-Year-Old Soil-Cement-Bentonite Slurry Wall in the Pocket Area to Examine the Behavior of Tree Roots

Trench sites were close to mature trees and were excavated in 2009 and 2010. In 2009, trenches were dug on both sides of a slurry wall adjacent to a black walnut tree measuring approximately 7 ft dbh that was growing on the landside levee crest about 35 ft from the slurry wall. These trenches revealed that roots from the walnut tree had been cut or broken at the edge of the wall

when the slurry wall was constructed. However, many of the cut ends of the roots had regenerated new branches one-quarter to three-quarters of an inch in diameter that penetrated the slurry wall a few inches and then divided into smaller roots that traveled laterally along the wall. The new extensions also penetrated the wall through fine cracks that formed about every 1 ft that Harder concluded must have formed as the wall dried, and the diameter of the largest root found penetrating the wall was about 0.5 in. Additionally, cottonwood roots were found adjacent to the wall, but the closest cottonwood trees were 160 ft and 110 ft away.

A second excavation site near valley oaks growing on the waterside yielded few roots, apparently because this species of oak trees does not extend roots very far upslope. A third site exposed both valley oak and cottonwood roots. Root travel from the oak trees was limited, but roots from the cottonwood trees growing 50–100 ft away penetrated the levee extensively. Just like the black walnut roots, cottonwood roots broken during slurry trenching regenerated branches that grew along and into the slurry wall, but these branches were larger, with diameters of 1.5 to 2.5 in. Based on observations at both sites, Harder (2012b) concluded that tree roots tended to grow along the walls and rarely penetrated them. Walls served as partial root barriers, but when cracks occurred, roots grew along and sometimes through them. The performance of modern, thicker cutoff walls as root barriers is unknown.

Gray (2009c) suggested that the penetration of the Pocket area slurry walls by tree roots documented by Harder et al. was not surprising, given the properties of the wall material and the opportunistic nature of tree root growth:

- The soil-cement-bentonite wall, when exposed by excavation, had a void ratio and porosity of 3.0 and 75%, respectively, leaving it very susceptible to desiccation, shrinkage, and cracking.

- Roots grow preferentially into soils offering adequate moisture relative to droughty zones. Roots also tend to avoid mechanical impedance such as obstacles and highly compacted soils. Accordingly, Gray (2009c) agreed with Harder that the roots penetrating the wall were exploiting and not causing the observed cracks in the cutoff wall.

Some European levees include sheet pilings inserted into slurry walls to provide barriers to roots and burrowing animals such as beaver. Kleber-Lerchbaumer (2012) described designs used in Bavaria that included sheet piles in the upper section of the levee to allow retention of woody vegetation on slopes. Washburn (2012) also noted the use of sheet piles in slurry walls as a potential treatment for Sacramento levees to ensure against root and burrow penetrations.

14.3 Data Gaps

Prototype-scale data are needed on the performance of various types of physical and chemical root barriers buried within levee embankments on root and burrow penetration over significant periods of time.

14.4 Points of Scientific Debate

No general method exists for ensuring that roots of plantings on levee slopes do not penetrate any designated part of the levee section. Methods for assessing existing or proposed levee cross sections for root exclusion are evolving. Because they are applied in the context of specific project or regional conditions, no generally applicable method is likely to emerge. To date, a scientific basis for setting the size of a root-free zone or for estimating the likely extent of roots of different woody species under different levee conditions has not been established. Approaches adopted for specific levee projects (e.g., see Section 14.2.1) tend to be conservative. It has been suggested that design of root-free zones include the consideration of the joint probability of treefall, high water, and maximum scour.

The best types of barriers and construction methods for existing and new levees to achieve economy and exclusion of risks due to vegetation and animals have not been established. Investigations have shown that tree roots can and do penetrate cracks in slurry cutoff walls in levees, but whether roots cause the cracks or exploit existing cracks has not been definitively answered. Slurry walls in levees free of tree roots have not been examined for cracking due to settling or desiccation, but note comments by Rice and Duncan (2010) regarding leaks in barriers in dams and their impacts on seepage.[27]

14.5 Potential Implications for Levee Vegetation Management

Considerable experience exists in the construction of levees with overbuilt sections with the objective of allowing trees on slopes without allowing roots to grow into the basic levee prism. However, recent findings regarding root architecture show that excluding roots from the basic levee prism requires limiting tree species on and within the vicinity of the levee to those known to have relatively compact root architectures (e.g., valley oak) rather than those with wide-ranging roots (e.g., cottonwood). Additional information regarding root architecture is provided in Chapter 2, " Woody Plant Root Architecture on and around Levees." An ongoing German research project features actively using certain species (shrubby willows) in levees to obtain benefits without associated liabilities.

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[27] Rice and Duncan (2010) provide a review of 30 case histories of dams that had seepage barriers in place for more than 10 years. They found that seepage barriers increase structural reliability in the majority of cases. However, they noted that leaks and cracks can develop in seepage barriers because of construction flaws, barrier deformation, and other cracking mechanisms. Consequences of barrier leaks include (1) decreased barrier effectiveness; (2) internal erosion of the barrier material; and (3) soil or rock erosion due to concentrated flow through the barrier. Finite element modeling showed that internal erosion of the barrier depends on many variables; in most cases, however, it was concluded that the seepage velocity through the crack would decrease as the crack widened, and erosion of the barrier material would be halted.

More promising exclusion of root penetration as well as burrow control may be achieved by incorporating subterranean barriers made of metal (sheet piling), mesh, rigid plastic, or geotextile in the levee embankment. Little documentation of the performance of barriers in flood- control levees is available.

Certain design features offer great potential for reducing uncertainty associated with woody vegetation on levees. Most of the design features discussed above have been at least considered for implementation in at least one project. However, all of these design features are costly, which would be taken into account in a “worst-first” approach to risk reduction as described above in Section 3.1, “Risk Analysis.”

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15 Summary and Conclusions

15.1 Overview

The key findings of this synthesis are presented in concise form below without reference to specific studies or documents. The reader is encouraged to refer to a specific topic heading in the report for citations. Levee vegetation is a component of a manmade ecosystem, and modification or management of vegetation on or adjacent to levee embankments is integrally related to levee function through direct and indirect linkages.[28] Full understanding of the role of vegetation requires contributions from many disciplines. A synopsis of findings from such a wide array of specialties is difficult to organize, but the sequencing of chapters is intended to guide the reader from "basic facts" about vegetation through risk considerations, concluding with practical applications for operations and design. Managers must give full consideration to the systemic effects of vegetation to select appropriate vegetation management measures, by assigning priorities within a full array of management actions based on risk prioritization and the efficient use of public resources.

Considerable progress has been made in understanding the effects of woody vegetation on levee seepage and slope stability. Much work remains in developing computer models of levees that include vegetation and are appropriate for routine applied use. Such models rely on an accurate depiction of root architecture and spatial distribution. Although noninvasive remotely sensed data would be quite valuable in this regard, efforts to develop technology suitable for widespread use on levees have not been successful. Root data require excavation, and root properties tend to vary by species and with site conditions.

Contributions from both research scientists and levee management professionals will be needed to translate the findings of this research into practices that can be selectively applied by levee managers to encourage the beneficial aspects of vegetation while mitigating the negative aspects. Levee vegetation management holds the potential to affect operations such as routine and emergency inspections and flood-fighting activities. Research remains to be done on these impacts and on methods to conduct inspections of vegetated levees or manage vegetation in ways that minimize impacts on flood fights. More information is available on the interactions among levee vegetation and surficial water erosion processes. Recently completed work on the forces required to uproot trees that typically grow on California levees indicates that there is generally little chance that sound trees on levees in central California will be uprooted by wind because winds necessary to overturn trees on levees in central California are rare. Furthermore, the likelihood that such a treefall would affect most (but not all) potential levee failure modes is

[28] Levee vegetation may directly contribute to levee function in a positive way by increasing slope stability. Indirectly, levee vegetation may facilitate progressive failure by hindering visual inspection or may reduce failure risk by making levees less attractive to burrowing rodents.

small. The exceptions to this would probably be windthrow of large trees located near the landside levee toe where there is already a seepage problem, and overturn of trees large enough relative to the levee to remove significant material from the prism, particularly if material is already removed or threatened by waterside erosion.

A key finding of California research is that burrowing mammal burrow densities appear to be associated with habitat types, with California ground squirrels favoring grassy habitats over habitats with trees or leaf litter. This is a critical finding from a risk reduction perspective because burrowing mammals are significantly more detrimental to levee reliability than any other risk factor studied related to levee vegetation.

U.S. national levee vegetation policy is controversial and currently being comprehensively reviewed as directed by the 2014 WRRDA. This offers the opportunity for policy to consider and incorporate new science. Levee vegetation policies have historically been strict, but have not been rigidly implemented or enforced in some locations for a variety of reasons. Among these are habitat restoration projects, operations and maintenance budget constraints, and uneven enforcement. This has produced a de facto regime favoring proliferation of volunteer woody species on and adjacent to levee slopes in some locations. Adaptive management of legacy levee vegetation on California levees focuses on appropriate clearing and thinning of woody vegetation for visibility and accessibility for inspections, maintenance, and flood fighting, along with identification and management of trees that pose an unacceptable threat to levee integrity. Much of the legacy levee vegetation was already in place at the time the federal project levees were turned over to the State of California in the 1950s. This also includes vegetation that was planted for mitigation as part of a cost-shared USACE project, as well as vegetation that remains in place as a requirement of the federal Endangered Species Act and other environmental laws. California's policy is reviewed and updated every 5 years, with the next update scheduled for 2017. International policies for levee vegetation management or removal vary. Nationally and internationally, flood systems managers will need to consider appropriate construction, repair, and maintenance of both new and legacy levees. With this synthesis report, the author and funders aim to assist policymakers and levee managers in the U.S. and abroad as they consider and incorporate new science regarding the interaction of vegetation and levees.

15.2 Risk and Levee Vegetation

Incorporation of factors related to the presence or absence of woody vegetation on and adjacent to levees into risk analyses is at a very primitive state at present, and few examples exist. However, the examples that do exist indicate that the effects of vegetation on total failure probability of central California levee systems are extremely small. This finding is confirmed by a forensic assessment of an extensive database of records of levee performance. Levee risk analyses may be refined as the state of the science for the topics discussed below improves. Current findings indicate that vegetation risk to levees is dwarfed by risk posed by other factors such as seismic events and underseepage.

Key Findings

- Certain levee design features such as root barriers and overbuilt embankments offer promise in reducing uncertainty associated with woody vegetation on levees. However, excavations to expose a 1-ft-thick, low-density slurry cutoff wall in Sacramento showed that roots occasionally penetrated the 1-ft-wide wall through vertical cracks that developed in the wall following construction.
- Brush layers were included in an experimental compacted levee embankment when it was built, and they survived and grew, indicating that vegetation may be used as a component of engineered earthen structures.
- Woody vegetation growing at or riverward of the levee waterside toe can provide significant benefits in damping waves, thus reducing associated erosion during high water.
- Effects of burrowing mammals on levees are significant. Based on habitat association studies, it appears likely that vegetation management practices can affect mammal population densities. Removal or prohibition of woody vegetation may increase hazards caused by animal burrows in some ecoregions.
- Subsurface morphology of trees growing on droughty levee embankments is different than for trees on hillslopes or plains.
- Most tree roots are confined to zones in the vicinity of the tree of origin and within 1 to 1.2 meters of the soil surface, but exceptions occur wherein roots greater than 2 cm appear at depths greater than 3 meters and more than 30 meters from the parent tree.
- Tree root decay rates vary with soil properties, tree species, and root diameter. Substantial decayed roots may remain for decades after tree death. Decaying roots have been reported to create tubular voids in cohesive soils. There have been no reports of decaying roots creating tubular voids in sandy soils. Some researchers have argued that soils occupied by dead roots underneath a dense stand of trees are quickly colonized and occupied by a new generation of roots from surrounding trees. Thus, slope stability would not be adversely affected by the root death of a single tree. However, this process would not occur if all trees were removed simultaneously.
- Windthrow potential for healthy trees growing on levees in California's Central Valley is small. Winds necessary to overturn healthy trees in the Central Valley are relatively rare events. Root pits created by treefall are of such a size that hazards from treefall are likely insignificant except for large trees in sensitive locations.
- Noninvasive detection of tree roots in levee embankments is generally beyond the state of the art, and certainly beyond the state of practice.
- Numerical models of levees that allow simulation of the effects of woody vegetation on slope stability and seepage require much field data and are not suitable for generalizing across a wide number or range of sites. In other words, models must be site specific. Accurate simulation of the effects of trees requires capture of the 3D aspects of the problem.
- Modeling the effects of tree roots on levee seepage is difficult, and simulation of the initiation and progression of piping erosion is at or beyond the state of the art.
- The effects of trees on levee soil properties, slope stability, and seepage-induced piping are small and hard to measure or simulate. Impacts can be beneficial or slightly detrimental depending on conditions and situation. A field experiment in California showed that seepage was slower in a levee slope containing a decaying tree stump than in an adjacent section of the same levee slope with only herbaceous vegetation.
- Review of California levee performance records shows no documented influence of levee vegetation on any known breaches. Vegetation had been either documented or perceived to have had an influence on levee performance in only 16 of 7,424 records.

15.3 Fundamental Research on Tree Roots

Understanding of the role of vegetation in riverine systems is rapidly expanding. Of particular note are recent findings regarding the belowground components of trees. Tree root systems are difficult to access, and their geometric complexity makes them difficult to analyze. However, a full understanding of many of the potential threats to levee integrity posed by trees requires reliable information about tree root architecture, root strength, and root decay.

15.3.1 Root Detection

Excavation of tree root systems is slow and expensive, and it destroys the studied subjects. A range of ingenious techniques has been developed for noninvasive detection of root architecture. Some methods hold potential for mapping individual roots, while others are likely limited to detecting zones of soil that have relatively high root densities. However, none of the tested noninvasive techniques have proven to function across a range of soil textures, densities, or moisture contents. Some techniques are limited to shallow depths. Anomalies such as voids, soil heterogeneity, and buried objects can confound results. Further, data require sophisticated analysis to generate useful information, and additional variation in results arises from root size, spacing, orientation, species, and root moisture content. Noninvasive root detection technology is not sufficiently developed for application to levee vegetation studies.

15.3.2 Root Architecture

Because noninvasive root detection and mapping is generally not adequate, tree root architecture definition usually requires some type of excavation to expose part or all of root systems. State-of-the-art technology includes excavation of roots using compressed air and then imaging the exposed roots using ground-based LiDAR scans. The resulting data are quite voluminous and must be subjected to sophisticated post-processing to yield useful information.

Root numbers, size, and biomass decrease sharply with horizontal distance from the tree and vertical distance from the surface. Exceptional cases of very long or very deep roots have been observed within or near levees. Most tree roots are confined to zones in the vicinity of the tree of origin and within 1 to 1.2 m of the soil surface, although exceptional roots greater than 2 cm appear at depths greater than 1 m and at significant distances from the tree. When viewed at the scale of 3–30 m, root distributions are highly heterogeneous and 3D, but tend to occur in general patterns that may be described as conical, disk-shaped, or cylindrical. Tree species and environmental factors such as soil texture, moisture, and slope are highly influential determinants of root architecture. Cottonwoods (*Populus* spp.) have been especially prominent in published studies for their wide-ranging, large roots, with large roots growing up to greater than 30 m from the parent tree.

15.3.3 Root Strength

Modeling the influence of trees growing on and adjacent to levee slopes on slope stability requires information about the strength and size and spatial distributions of tree roots. Spatial distributions may be addressed via root architecture studies, while field and laboratory tests are used to measure root tensile and bending strength. Available data show that root tensile strength

per unit cross-sectional area varies only slightly among tree species, but shows an inverse exponential relationship with root diameter. Differences from site to site caused by differences in hydrology, soils, climate, tree species, age, and spatial distribution may also be important.

15.3.4 Root Decay

Soil under trees normally contains high densities of roots, both living and dead. The root decay rate varies with soil properties, tree species, and root diameter. As roots decompose in cohesive soils, they may create tubular voids or pipes. Such voids may allow water penetration that facilitates seepage and piping or exerts elevated pore pressures that destabilize slopes. As roots decompose in cohesionless soils, voids left by root decay are typically filled in by the soil. A field experiment in California on a typically sandy levee showed that seepage was slower in a levee slope containing a decaying tree stump than in an adjacent section of the same levee slope with only herbaceous vegetation.

Some workers argue that decaying roots are rapidly colonized by living roots from adjacent trees, but this process obviously cannot occur when all trees are cleared. Clear-cutting of slopes (wholesale tree removal) can trigger landslides because of the concentration of these effects and the loss of root contributions to slope stability as the roots decay. Field tests on levees have revealed that roots may persist for decades following tree death. Decay rates vary from site to site based on climate and soil type, while variations in decay rates at a given site are related to tree species and root diameter.

15.4 Potential Influence of Vegetation on Levee Risk Factors

15.4.1 Treefall

Trees growing on or immediately adjacent to levees create pits when overturned and uprooted by wind or water. Research approaches include measuring forces required to pull over living trees using mechanical winching systems, although forces exerted on trees by such systems do not exactly replicate the dynamism of wind loads. Published results of such tests are associated primarily with conifers growing in forested stands. Recent CLVRP results for valley oaks and cottonwoods show trends consistent with earlier work by others. Forces (moments) required to topple trees were directly proportional to tree size, as were the areas of pits left by overturned trees. Small trees are the most readily overturned but produce the smallest pits. Overturning trees with dbh less than 1 m are unlikely to remove enough soil from the levee prism to endanger levees with crown widths greater than 6 m.

In general, large forces were required to topple trees, and winds large enough to generate such forces are rare in California’s Central Valley.

15.4.2 Burrows

Burrowing animals, especially California ground squirrels and Botta’s pocket gophers, are ubiquitous in levees in the lower Sacramento River basin. Burrowing animals pose a known, serious risk to earthen levee embankments. Burrows can greatly accelerate movement of water

through levees under hydraulic loading and have been implicated in levee failures. Seepage experiments and forensic investigations of failed levees suggest that animal burrows are much more dangerous to levee embankments than tree roots. The greatest danger is associated with networks of burrows or voids that create a continuous penetration through the embankment. Burrows with waterside entrances also pose a hazard as they shorten the time to local saturation.

Some levees are maintained by periodically pumping grout into burrow entrances. Research at two California levee sites indicated that filling burrows with grout was only partially effective in removing the hazard caused by burrows, because grout filled only 76% and 82% of the burrow volumes. The response of burrowing mammals to vegetation management varies from one ecoregion to another, but the occurrence and abundance of California ground squirrels have a significant negative association with leaf litter and woody vegetation. Conversion of levee vegetation from woody to grassy cover in the Sacramento Valley may lead to increased abundance of ground squirrels and pocket gophers. Ground squirrel burrow abundance also displays association with vegetation at the landscape scale, with burrows less common in levee slopes bordered by grasslands and more common in levees bordered by fruit and nut crops.

15.4.3 Water Erosion

During floods, levee waterside slopes may be threatened by erosion caused by river currents or waves. Levee crests and landside slopes may be eroded if the embankment is overtopped by waves or by the flood surge. Empirical observations indicate that erosion of waterside slopes can be mitigated by stands of woody vegetation growing on the waterside berm or floodplain. Some observers have suggested that isolated trees, fallen trees, or blocks of trees may promote local scour of waterside slopes by deflecting and accelerating flows, but no documented cases of resulting levee failure were found in the literature. Local scour around individual trees or blocks of vegetation is subject to site-specific controls such as the duration of flooding, the erodibility of the underlying soils, and the magnitude of local velocities. The erodibility of soils may be modified by roots and shielded by ground cover or low flexible, stems of woody species. Standard approaches are needed for assessing positive and negative effects of woody vegetation on water erosion of levees.

15.4.4 Seepage and Piping

During flood events, concentrated seepage may trigger progressive piping that compromises levee integrity. Roots from trees growing on or immediately adjacent to levees potentially create preferential seepage paths or voids. Pits left by uprooted trees can shorten seepage paths, and thus also invite piping. Even if piping does not occur, root-induced changes to seepage patterns can modify soil moisture within the levee embankment, degrading or improving slope stability. Data and models suggest that local seepage patterns, pore pressures, and hydraulic gradients may be modified by trees if their roots modify the local hydraulic conductivity, but implications at the larger scale and thus for overall levee integrity are minimal. Model simulations indicate that most pronounced effects of enhanced seepage on levee integrity occur when a zone of elevated hydraulic conductivity is placed at the landside levee toe.

Forest cover tends to foster high levels of soil permeability, but research to date on the effects of trees or groups of trees on levee soil hydraulic conductivity on levee slopes has failed to demonstrate a consistent pattern. Numerical models purporting to show the effect of trees on seepage in levees are based on the assumption that trees growing on levees affect hydraulic conductivity at a micro or macro scale. This assumption is not supported by existing data, however. Macropores and flow concentration are caused by many processes in addition to root growth and death, most notably by animal burrowing. Existing data show that California ground squirrel burrow densities tend to be higher for levee slopes without trees or leaf litter.

The effects of living and dead trees on soils are local and complex and are quite difficult to simulate in numerical models. 2D representations of subterranean components of trees tend to overstate their influence, but 3D models have seen limited use in real applications because of their extreme complexity. Sophisticated 3D models that simulate deformation of earthen structures offer high temporal and spatial resolution and are promising but currently are research tools and are not suitable for general use by practitioners.

15.4.5 Slope Stability

Levees sometimes fail when slopes collapse or slide. These slope failures generally occur whenever the driving forces (e.g., the weight of the soil and differential pore-water pressure) exceed resisting forces provided by embankment soils. Additional driving forces may include dynamic forces from earthquakes and vehicle traffic. Resistance is lowered by hydraulic or pore-water pressures that can develop under certain conditions. Analyses of the likelihood of levee slopes to fail are based on mathematical models that require input data for levee geometry, levee and floodplain soil characteristics, and surface and groundwater elevations. These analyses may be static (for a single instant in time) or dynamic (conditions over a period of time). Because soil strength is strongly influenced by soil moisture levels and seepage, slope stability analyses are dependent on assumed or computed seepage, and seepage analyses are typically prerequisite to stability analyses.

The influence of vegetation on slope stability is modeled by assuming modifications in soil moisture and seepage caused by roots, increasing soil cohesion in rooted zones, and increasing loading forces to reflect the weight of the vegetation and loads imposed by wind. Measured or assumed information about the spatial distribution of roots and root strength may be incorporated into slope stability simulations in several ways. The fiber bundle model approach appears to be the current state of the art. Although trees and their roots are complex, 3D entities, practical computations are usually 2D and therefore imperfectly capture vegetative effects. Representation of vegetation effects in 2D models must be completed carefully to avoid overstating or understating the influence of vegetation. Most models are deterministic; they compute a single Fs against failure. More recent models are probabilistic; they take into account uncertainties in soil properties and other parameters. More sophisticated 3D models that simulate variably saturated flow and elastic-plastic deformation using nonlinear continuum mechanical models are gradually coming into more widespread use, and may allow more realistic simulation.

Current model representation of the effects of wind loading on the stability of treed levee slopes is unsatisfactory. Available analyses indicate that the effects of trees on levee slope Fs vary

widely with site conditions. Research indicates woody vegetation influences slope stability in a positive fashion except under the most extreme of assumed conditions. Numerous site-specific variables come into play when computing the exact effect of a given tree or pattern of tree growth on Fs.

15.5 Levee Vegetation and Operations

15.5.1 Inspection

Federal regulations require periodic inspection of levees to detect flaws such as erosion, slumping, and other signs of distress. Many inspections are performed from vehicles driven along the levee crown with personnel watching both sides, but detailed inspections conducted at 5-year intervals by USACE personnel must be completed by a multidisciplinary team "physically walking the levee alignment and associated inspection areas." One key rationale for prohibiting trees and shrubs on and immediately adjacent to levees is their perceived negative impact on visibility and accessibility for inspection. Suggestions for addressing these concerns include the use of walking inspectors and application of guidelines for cutting and trimming trees and shrubs to allow views under the canopy. There are many international guidelines for thinning and trimming vegetation to maintain access and visibility (e.g., those promulgated by DWR and the Environment Agency of the United Kingdom). No published scientific research was found on the effects of vegetation on routine levee inspection, or of the efficacy of the methods suggested for addressing inspection concerns without vegetation removal.

The effect of woody vegetation on and adjacent to levees on levee inspection will remain controversial in the absence of data and information. Techniques have been suggested, though not yet studied, to avoid or minimize vegetation impacts on inspections. Among these techniques are the use of walking inspectors, well-enforced vegetation management guidelines, and the use of special sensors to detect problems and supplement visual inspection.

15.5.2 Flood Fighting

Flood-fighting activities require that levee embankments be intensively monitored for signs of leakage, overtopping, erosion, or other forms of distress. When problems are imminent, personnel, material, and equipment must be rapidly deployed to provide temporary erosion protection, control seepage, and sometimes raise levees or build temporary flood protection structures. Some policies regarding clearing vegetation for flood fighting are based on a conservative approach to ensuring unrestricted levee access and visibility. Evidence regarding adverse and beneficial effects of woody vegetation on flood-fighting activities is extremely limited. No research or systematic studies of current practice were found on this topic.

15.6 Recommendations for Future Research

The research project publications reviewed for this report contain numerous specific recommendations for future work. Most focus on the problem at hand: assessment of the impact

of existing trees (both volunteered and planted) on older levees. Concerns for legacy systems with trees are noted above, and among these are the need for more quantitative information to provide a scientific basis for managing vegetation to allow inspection and flood fighting. Clearly, if wholesale removal of large numbers of trees from levee slopes were to occur, more information is needed to develop protocols for tree removal and slope restoration that minimizes the risks of slope failure and undesirable seepage.

In addition to supporting Sitar's risk assessment study in 2015–2016, DWR has expressed that its primary research interests are (1) applying existing research to State levee management policy and (2) developing a methodology to collect field data during normal operations and maintenance and flood fighting that can support future analysis if needed. This methodology will be applied by DWR over time to document data from fallen trees on levees and levee performance incidents in which trees appear to have had either positive or negative impacts.

Despite the urgency of problems posed by legacy systems, this writer's view is that research strategy and funding should prioritize long-term issues such as design and management of new levees that include vegetation as structural components. Although numerical simulation of existing volunteer vegetation is interesting and useful, research strategy and funding should anticipate the potential for future levee design and management to incorporate vegetation as structural levee components, and therefore should study the associated issues, including the need to develop superior technology for inspection and flood fighting in the presence of woody vegetation. Vegetation should be included in design analyses, and species and cultivars with desirable engineering and ecological properties should be identified. The use of levee setbacks, overbuilt sections, root barriers, and biotechnical treatment of slopes all are worthy of additional research.

Robust risk assessments that include various vegetation scenarios will help inform future policy and may represent a step in resolving issues regarding levee vegetation.

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17 References

Allen, S. B., J. P. Dwyer, D. C. Wallace, and E. A. Cook. 2003. "Missouri River flood of 1993: Role of woody corridor width in levee protection." *Journal of the American Water Resources Association* 39(4):923–933.

Ang, A. H.-S., and C. A. Cornell. 1974. "Reliability bases of structural safety and design." *Journal of Structural Engineering* 100(9):1755–1769.

Ang, A. H.-S., and W. H. Tang. 1984. *Probability Concepts in Engineering Planning and Design, Vol. II—Decision, Risk, and Reliability*. Wiley, New York, New York.

Apel, H., A. H. Thieken, B. Merz, and G. Bloschl. 2004. "Flood risk assessment and associated uncertainty." *Natural Hazards and Earth System Sciences* 4:295–308.

[ASCE] American Society of Civil Engineers. 2010. *So You Live Behind a Levee! What You Should Know to Protect Your Home and Loved Ones from Floods*. Reston, Virginia.

Bachmair, S., M. Weiler, and P. A. Troch. 2012. "Intercomparing hillslope hydrological dynamics: Spatio-temporal variability and vegetation cover effects." *Water Resources Research* 48(5).

Bayoumi, A., and M. A. Meguid. 2011. "Wildlife and safety of earthen structures: A review." *Journal of Failure Analysis and Prevention* 11:295–319.

Bean, T. 2012. "Vegetation influence on levee operations: Inspections, flood fighting, and maintenance." Transcript of remarks before Levee Vegetation Research Symposium 2012, August 29, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_08_29_Transcripts_Panel_2.pdf. Accessed February 13, 2014.

Bernhardt, E. S., and M. A. Palmer. 2011. "River restoration: The fuzzy logic of repairing reaches to reverse catchment scale degradation." *Ecological Applications* 21(6):1926–1931.

Berry, A. M., and S. M. Chung. 2012. "Trees on levees: The controversy and what science has to say." PowerPoint presentation presented to the American Society of Consulting Arborists on November 30, 2012.

Beven, K., and P. Germann. 2013. "Macropores and water flow in soils revisited." *Water Resources Research* 49(6):3071–3092.

Bransby, M. F., S. B. Mickovski, R. Sonnenberg, A. G. Bengough, and P. D. Hallett. 2006. "Stabilisation of slopes by vegetation reinforcement." In C. W. W. Ng, Y. H. Wang, and L. M. Zhang (eds.), *Proceedings of the Sixth International Conference on Physical Modelling in Geotechnics.* CRC Press, Taylor & Francis Group.

Buer, S., H. Brown, K. Yamaski, M. Vennetier, C. Neudeck, A. M. Berry, and D. H. Gray. 2012. "Recent experiences with levee vegetation removal." Transcript of remarks before Levee Vegetation Research Symposium 2012, August 30, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_08_30_Session_3.pdf. Accessed April 14, 2014.

Burnett, R. 2007. "Flood fighting and levee vegetation." Transcript of remarks before 2007 Levee Vegetation Research Symposium, August 28–29, 2007. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/protection/&bios/LevVegSymBurnetttranscript.pdf. Accessed February 13, 2014.

Burnett, R., E. Bryson, and X. Li. 2012. *Flood Fighting Methods.* California Department of Water Resources, Division of Flood Management, Flood Operations Branch. Sacramento, California.

California Science Team. 2010. *Comments on ERDC Seepage and Slope Stability Model*. Draft document. California Levee Vegetation Research Program, Sacramento Area Flood Control Agency, Sacramento, CA.

Carter, L. W., and G. L. Anderson. 1984. "Riparian vegetation on flood control project levees: constraints and opportunities." Pages 548–550 in R. E. Warner and K. M. Hendrix (eds.), *California Riparian Systems: Ecology, Conservation and Productive Management.* University of California Press, Berkeley.

Central Valley Flood Protection Board. 2009. "California's Central Valley Flood System Improvement Framework." Central Valley Flood Protection Board, Sacramento, California. Available at http://www.cvfpb.ca.gov/docs/031209flood_improvement.pdf. Accessed December 16, 2013.

Chambers, J. L., T. J. Dean, M. S. Hughes, C. B. Allen, F. Wu, and W. Wright. 2008. *Documentation and Analysis of Tree Root Extent and Behavior along and in Levees and Floodwalls in the New Orleans District.* New Orleans District, U.S. Army Corps of Engineers. Final Report No. W912P8-07-D-0040. New Orleans, Louisiana.

Chen, Z. Q. R., M. L. Kavvas, H. Bandeh, E. Tan, J. Carlon, T. Griggs, and S. Lorenzato. 2009. *Study of the Roughness Characteristics of Native Plant Species in California Floodplain Wetlands.* Report to the California Department of Water Resources. University of California, Davis J. Amorocho Hydraulics Laboratory, Davis, California.

Chung, S. M. 2013. *Tree Root System Architecture on Levee Slopes: 3D Quantitative Model Building, Biomass, Estimation, and Spatial Pattern Characterization*. Doctoral dissertation, University of California, Davis. Davis, California.

Chung, S. M., and A. M. Berry. 2012. "Tree root architecture: Patterns and geotechnical roles in levees." Presentation to Levee Vegetation Research Symposium 2012, August 28, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Chung_Presentation2.pdf. Accessed October 30, 2013.

Chung, S. M., G. W. Bawden, K. Keightley, S. Bond, J. M. Lichter, and A. M. Berry. 2013. *Building Quantitative 3D In-situ Spatial Models of Tree Root Systems Using Ground-Based Tripod LiDAR Technology.* Draft manuscript. University of California, Davis.

[CIRIA] Construction Industry Research and Information Association. 2013. *International Levee Handbook.* London, U.K.

[CLVRP] California Levee Vegetation Research Program. 2011. *Informational Circular No. 2: Summary of Research Completed to Date*, December 12, 2011.

[CLVRP] California Levee Vegetation Research Program. 2013. *California Future Research Needs/Priorities*, December 13, 2011.

Cobos-Roa, D., M. Shriro, N. Sitar, and J. Bray. 2012a. "Mammal burrow characterization and effectiveness of burrow grouting." Presentation to Levee Vegetation Research Symposium 2012, August 29, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Cobos-Roa_Presentation_Day2a.pdf. Accessed June 25, 2013.

Cobos-Roa, D., M. Shriro, N. Sitar, and J. Bray. 2012b. *Modeling the Influence of Trees on Seepage Behavior of Levees.* Presentation to Levee Vegetation Research Symposium 2012, August 29, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/2012_Symposium_Presentations_Day2.html. Accessed July 30, 2013.

Cobos-Roa, D. C., M. Shiro, N. Sitar, J. Bray, G. W. Bawden, J. Lichter, and R. Evans. 2012c. *3-D Stratigraphy and Root Geometry from Trench and Ground-Based LiDAR Mapping.* 2012 GeoCongress Conference: State of the Art and Practice in Geotechnical Engineering, ASCE, 25–29 March, Oakland, California. American Society of Civil Engineers, Reston, Virginia.

Cobos-Roa, D., M. Shriro, N. Sitar, and J. Bray. 2014a. *Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 1—Review of Literature and Case Histories*. Department of Civil and Environmental Engineering, University of California, Berkeley.

Cobos-Roa, D., M. Shriro, N. Sitar, and J. Bray. 2014b. *Influence of Tree Roots and Mammal Burrowing Activity on Levee Integrity: Volume 4. Field Evaluation of Burrowing Animal Impacts and Effectiveness of Remedial Measures*. University of California, Berkeley.

Coder, K. D. 2010. *Root Strength & Tree Anchorage.* University of Georgia Warnell School of Forestry & Natural Resources monograph publication WSFNR10-19. Athens, Georgia.

Corcoran, M. 2012. *Overview of Initial Research into the Effects of Woody Vegetation on Levees*. U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, Mississippi. Presentation to Levee Vegetation Research Symposium 2012, August 27, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Corcoran_Presentation_Day1.pdf. Accessed February 11, 2014.

Corcoran, M. K., D. H. Gray, D. Biedenharn, C. D. Little, J. R. Leech, F. Pinkard, P. Bailey, and L. T. Lee. 2010. *Literature Review: Vegetation on Levees*. Technical Report Number ERDC SR-10-2. U.S. Army Engineer Research and Development Center. Vicksburg, Mississippi.

Corcoran, M. K., J. F. Peters, J. B. Dunbar, J. L. Llopis, F. T. Tracy, J. Wibowo, J. E. Simms, C. E. Kees, S. K. Mckay, J. C. Fishenich, M. W. Farthing, M. E. Gylnn, B. A. Robbins, R. C. Strange, M. T. Schultz, J. U. Clarke, T. E. Berry, C. D. Little, and L. T. Lee. 2011. *Initial Research into the Effects of Woody Vegetation on Levees."* ERDC SR-10-2. U.S. Army Corps of Engineers, Engineer Research and Development Center. Vicksburg, Mississippi.

Cunny, R. W. 1987. *Inspection and Control of Levee Underseepage during Flood Fights*. Technical Report REMR-GT-5. U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Daar, S., W. Klitz, and W. Olkowski. 1984. *The Role of Vegetation in an Integrated Pest Management Approach to Levee Management.* University of California Press, Berkeley and Los Angeles, California.

Danjon, F., and B. Reubens. 2008. "Assessing and analyzing 3D 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. 2008. "Using three-dimensional plant root architecture in models of shallow-slope stability." *Annuals of Botany* 101:1281–1293. doi: 10.1093/aob/mcm199.

Day, S. D., E. P. Wiseman, S. B. Dickinson, and J. R. Harris. 2010. "Tree root ecology in the urban environment and implications for a sustainable rhizosphere." *Arboriculture and Urban Forestry* 36(5):193–205.

Dixon, J. 1922. “Rodents and reclamation in the Imperial Valley.” *Journal of Mammalogy* 3(3):136–146.

Douglas, G. B., I. R. Mcivor, A. K. Manderson, J. P. Koolaard, M. Todd, S. Braaksma, and R. A. J. Gray. 2013. “Reducing shallow landslide occurrence in pastoral hill country using wide-spaced trees.” *Land Degradation and Development* 24:103–114.

Duncan, J. M. 1999. *Review of Corps of Engineers Design for Rehabilitation of the Perimeter Dikes around Cross Lake, Minnesota*. Report submitted to St. Paul District, U.S. Army Corps of Engineers. Blacksburg, Virginia.

[DWR] California Department of Water Resources. 2007. 2007 California Flood Legislation Summary. Sacramento, California. Available at http://water.ca.gov/legislation/2007-reference.pdf. Accessed May 23, 2015.

[DWR] California Department of Water Resources. 2012a. *Central Valley Flood Protection Plan: A Path for Improving Public Safety, Environmental Stewardship, and Long-Term Economic Stability*. Sacramento, California.

[DWR] California Department of Water Resources. 2012b. *Urban Levee Design Criteria*. FloodSAFE California, Sacramento, California.

Dwyer, J. P., D. C. Wallace, and D. R. Larsen. 1997. “Value of woody river corridors in levee protection along the Missouri River in 1993.” *Journal of the American Water Resources Association* 33(2):481–489.

Ellison, M. J. 2005. “Quantified tree risk assessment used in the management of amenity trees.” *Journal of Arboriculture* 31(2):57–65.

Farthing, M. W., C. E. Kees, M. K. Corcoran, and J. E. Peters. 2011. *Finite Element Analysis of Levees with Woody Vegetation.* American Geophysical Union Fall Meeting. Available at http://adsabs.harvard.edu/abs/2011AGUFM.H33G1390F. Accessed August 1, 2013.

Fathi-Moghadam, M. 2007. “Characteristics and mechanics of tall vegetation for resistance to flow.” *Journal of Biotechnology* 6(4):475–480.

[FEMA] Federal Emergency Management Agency. 2008. “The NFIP and levees: Frequently asked questions.” Available at https://www.floodsmart.gov/toolkits/levee/files/pdfs/faq_levee_jan08.pdf. Accessed July 22, 2014.

[FEMA] Federal Emergency Management Agency. 2012. “History of levees.” Available at http://www.fema.gov/media-library-data/20130726-1807-25045-3487/history_of_levees.pdf. Accessed July 1, 2014.

Fitzgerald, W. S., and R. E. Marsh. 1986. "Potential of vegetation management for ground squirrel control." In *Proceedings of the Twelfth Vertebrate Pest Conference*, March 4, 5, and 6, 1986. Available at http://digitalcommons.unl.edu/vpc12. Accessed June 25, 2013.

Fitzgerald, W. S., and R. A. Thompson. 1988. "Problems associated with beaver in stream or floodway management." In *Proceedings of the Thirteenth Vertebrate Pest Conference*, March 1988. Available at http://digitalcommons.unl.edu/vpcthirteen/40/. Accessed July 24, 2013.

Fox, G. A., D. M. Heeren, G. V. Wilson, E. J. Langendoen, A. Fox, and M. L. Chu-Agor. 2009. "Numerically predicting seepage gradient forces and erosions: Sensitivity to soil hydraulic properties." *Journal of Hydrology* 389:354–362.

Fraser, A. I., and J. B. H. Gardiner. 1967. "Rooting and stability in Sitka spruce." *Forestry Commission Bulletin* 40:1–28. Forestry Commission, Her Majesty's Stationery Office, London, U.K.

Galinski, W. 1989. "A windthrow-risk estimation for coniferous trees." *Forestry* 62(2):139–146.

Galloway, G. E. 2008. "Levees in history and levees today: The levee challenge." Background presentation to the National Committee on Levee Safety. U.S. Army Corps of Engineers National Conference Center, Lansdowne, Virginia.

Genet, M., N. Kokutse, A. Stokes, T. Fourcaud, X. Cai, J. Ji, and S. B. Mickovski. 2008. "Root reinforcement in plantations of *Cryptomeria japonica D. Don*: Effect of tree age and stand structure on slope stability." *Forest Ecology and Management* 256(8):1517–1526.

Genet, M., A. Stokes, T. Fourcaud, X. Cai, and Y. Lu. 2006. "Soil fixation by tree roots: Changes in root reinforcement parameters with age in *Cryptomeria Japonica D. Don.* Plantations." In H. Marui, T. Marutani, N. Watanabe, et al. (eds.), *Disaster Mitigation of Debris Flows, Slope Failures and Landslides: Proceedings of the INTERPRAEVENT International Symposium*, September 25–27, 2006, Niigata, Japan. Universal Academy Press, Inc., Tokyo, Japan.

Genet, M., A. Stokes, F. Salin, S. B. Mickovski, T. Fourcaud, J. F. Dumail, and R. van Beek. 2005. "The influence of cellulose content on tensile strength in tree roots." *Plant and Soil* 278:1–9.

Gianetta, I., S. Massimiliano, G. Christian, and W. Lammeranner. 2013. "Modeling and analysis of the vertical roots distribution in levees—a case study of the third Rhone correction." In *Proceedings of the EGU General Assembly 2013*, held 7–12 April, 2013 in Vienna, Austria, id. EGU2013-6258.

Glynn, M. E., and J. Kuszmaul. 2004. *Prediction of Piping Erosion along Middle Mississippi River Levees—An Empirical Model.* Technical Report Number TR-04-12. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Gray, D. H. 1984. *Investigation of Adequacy of Hazardous Waste Landfill and Cover Design Criteria.* Report submitted to the Toxic Substances Control Commission, State of Michigan, April 1984.

Gray, D. H. 2009a. "The hazards and risks of tree removal." Unpublished memorandum submitted to the California Levee Vegetation Research Program, Sacramento, California.

Gray, D. H. 2009b. "The effect of woody vegetation removal on the hydrology and stability of slopes." Unpublished memorandum submitted to the California Levee Vegetation Research Program, Sacramento, California. Available at ftp://ftphost3.water.ca.gov/outgoing/FMO/Veg_on_Levees/Literature%20Reviews/Effects%20of%20Tree%20Removal.pdf. Accessed April 14, 2014.

Gray, D. H. 2009c. "Affinity of tree roots for clay cutoff walls embedded in sandy levees." Sacramento Area Flood Control Agency. Unpublished report. Ann Arbor, Michigan.

Gray, D. H. 2009d. "Literature review synopsis: Effect of woody vegetation removal on the hydrology and stability of slopes." Unpublished paper.

Gray, D. H. 2013. "Role and influence of macropores on hydraulic conductivity and flow through earthen barriers." Memorandum to files as consultant to California Levee Vegetation Research Program, Sacramento, California. Ann Arbor, Michigan.

Gray, D. H., and D. Barker. 2004. "Root-soil mechanics and interactions." Pages 113–124 in S. J. Bennett and A. Simon (eds.), *Riparian Vegetation and Fluvial Geomorphology.* American Geophysical Union, Washington, D.C,

Gray, D. H., A. MacDonald, T. Thomann, I. Blatz, and F. D. Shields. 1991. *The Effects of Vegetation on the Structural Integrity of Sandy Levees.* Repair, Evaluation, Maintenance, and Rehabilitation Research Program, Technical Report REMR-EI-5. U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Gui, S., Zhang, R. and Xue, X. 1998. "Overtopping reliability models for river levee." *Journal of Hydraulic Engineering* 124:1227–1234.

Guo, L., J. Chen, X. Cui, B. Fan, and H. Lin. 2013a. "Application of ground penetrating radar for coarse root detection and quantification: A review." *Plant and Soil* 362:1–23.

Guo, L., H. Lin, B. Fan, X. Cui, and J. Chen. 2013b. "Impact of root water content on root biomass estimation using ground penetrating radar: Evidence from forward simulations and field controlled experiments." *Plant and Soil* 371:503–520.

Hales, T. C., C. R. Ford, T. Hwang, J. M. Vose, and L. E. Band. 2009. "Topographic and ecologic controls on root reinforcement." *Journal of Geophysical Research* 114:1–17.

Hales, T. C., C. Hawthorne-Cole, L. Lovell, and S. L. Evan. 2013. "Assessing the accuracy of simple field based root strength measurements." *Plant Soil* 372(2013):553–565.

Harder, L. 2012a. "Engineering design and vegetation management solutions to safely allow retention of some vegetation on levees." Remarks as part of panel discussion at Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_08_30_Transcript_Panel_4.pdf. Accessed March 25, 2014.

Harder, L. F. 2012b. "Investigation of tree root penetration into levees and a SCB slurry cutoff wall." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Harder_Presentation.pdf. Accessed October 29, 2013.

Harder, L. F. 2012c. "Investigation of tree root penetration into levees and a SCB slurry cutoff wall." Transcript of presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Harder_Transcript.pdf. Accessed September 1, 2015.

Harder, L. F. 2012d. "Concerns about ERDC slope stability evaluations performed to determine the effects of woody vegetation on levees." Unpublished memo.

Harder, L. F., R. Kroll, E. F. Buck, M. Inamine, and A. M. Berry. 2011. *Investigation of Tree Root Penetration into Levee Soil-Cement-Bentonite Slurry Wall—Part II.* California Department of Water Resources and Sacramento Area Flood Control Agency, Sacramento, California.

Harder, L. F., R. Kroll, V. Claassen, P. Buck, and A. M. Berry. 2010. "Investigation of tree root penetration into a levee soil-cement-bentonite slurry cutoff wall." California Department of Water Resources and Sacramento Area Flood Control Agency. Sacramento, California.

Harder, L. F., N. Vroman, G. L. Sills, C. Groves, and J. R. Kelley. 2009. "Inspection of levee distress and breaches during the spring 2008 Midwest flood." Presentation to Society of American Military Engineers, Sacramento, California. Available at http://www.samesacramento.org/calendar/waterconference_PDFs/Harder_Sess8_102209.pdf. Accessed March 10, 2015.

Harteveld, C., R. Guimaraes, I. S. Mayer, and R. Bidarra. 2010. "Balancing play, meaning, and reality: The design philosophy of levee patroller." *Simulation and Gaming* 41(3):316–340.

Hertzberg, R. 1954. “Wave-wash control on Mississippi River levees.” *Transactions of the ASCE* 119(2688):628–638.

Hirano, Y., M. Dannoura, K. Anon, T. Igarashi, M. Ishii, K. Yamese, N. Makita, and Y. Kanazawa. 2009. “Limiting factors in the detection of tree roots using ground-penetrating radar.” *Plant and Soil* 319:15–24.

Holmes, R. R., and K. Dincola. 2010. *100-Year Flood—It’s All About Chance*. General Information Product 106. U.S. Geological Survey, Reston, Virginia.

Hounjet, M., J. Maccabiani, R. van der Bergh, and C. Harteveld. 2009. “Application of 3D serious games in levee inspection education.” In P. Samuels, S. Huntington, W. Allsop, and J. Harrop, *Flood Risk Management: Research and Practice.* Taylor & Francis Group. London, U.K.

Huang, W., R. Millet, S. Shewbridge, J. Perri, J. Vargas, M. Inamine, and S. Mahnke. 2010. “Levee erosion screening process.” Pages 305–15 in S. E. Burns, S. K. Bhatia, C. M. C. Avila, and B. E. Hunt (eds.), *Scour and Erosion: Proceedings of the Fifth International Conference on Scour and Erosion (ICSE-5),* San Francisco, California, November 7–10, 2010. American Society of Civil Engineers, Reston, Virginia.

Huang, Y. W. 2004. “Discussion on the surplus elevation for the Pearl River in Guangzhou City.” *Pearl River* 3.

Huang, Y. W., and X. Yu. 2007. “Engineering aspects of the south China levee system with implications for the reconstruction of the New Orleans levee system.” Pages 1–9 in T. C. Siegel, R. Luna, T. Hueckel, and L. Laloui (eds.), *Computer Applications in Geotechnical Engineering.* ASCE Geotechnical Special Publication No. 157. American Society of Civil Engineers, Reston, Virginia.

Hynson, J. R., P. R. Adamus, J. O. Elmer, and T. DeWan. 1985. *Environmental Features for Streamside Levee Projects.* Technical Report E-85-7. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Hynson, J. R., P. R. Adamus, J. O. Elmer, T. DeWan, and F. D. Shields. 1985. *Environmental Features for Streamside Levee Projects.* Environmental and Water Quality Operational Studies. Technical Report E-85-7. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

[ILIT] Independent Levee Investigation Team. 2006. *Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005*. National Science Foundation. Available at http://www.ce.berkeley.edu/projects/neworleans/report/intro&summary.pdf. Accessed February 11, 2014.

Jackson, R. B., J. Canadell, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze. 1996. "A global analysis of root distributions for terrestrial biomes." *Oecologia* 108(3):389–411.

James, L. A., and M. B. Singer. 2008. "Development of the lower Sacramento Valley flood-control system: An historical perspective." *Natural Hazards Review* 9(3):125–135, doi:10.1061/(ASCE)1527-6988(2008)9:3(125).

Johnson, E. 2011. "Levee scour protection for storm waves." Abstract OS33C-1689 presented at 2011 Fall Meeting, American Geophysical Union, San Francisco, California, December 5–9, 2011.

Jones, C. E., G. W. Bawden, S. Deverel, J. Dudas, S. Hensley, and S.-H. Yun. 2012. "Study of movement and seepage along levees using DINSAR and the airborne UAVSAR instrument." In C. Notarnicola, S. Paloscia, and N. Pierdicca (eds.), *Proceedings of SPIE* 8536, *SAR Image Analysis, Modeling, and Techniques XII*, 26–27 September 2012, Edinburgh, U.K.

Kabir, N., and F. Bean. 2011. *The Influence of Vegetation on Levee Past Performance—A Review of Historic Data Based on the Levee Evaluation Program Database*. Report to the California Levee Vegetation Research Program. URS Corporation, Sacramento, California.

Kane, B., M. Pavlis, J. R. Harris, and J. R. Seiler. 2008. "Crown reconfiguration and trunk stress in deciduous trees." *Canadian Journal of Forestry Research* 38(6):1275–1289.

Kees, C., M. Farthing, and C. Dawson. 2008. "Locally conservative, stabilized finite element methods for variably saturated flow." *Computer Methods in Applied Mechanics and Engineering* 197:4610–4625.

Kees, C., M. Farthing, J. Peters, and M. Corcoran. 2012. "Using the Proteus toolkit to simulate 3d levee statics and dynamics." U.S. Army Corps of Engineers. Presentation to Levee Vegetation Research Symposium 2012, August 28–30, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Kees_Presentation.pdf. Accessed March 10, 2015.

Kelley, R. 1989. *Battling the Inland Sea*. University Press. Berkeley and Los Angeles, California.

Khalilzad, M., M. A. Gaber, and M. E. Hynes. 2013. "Effects of woody vegetation on seepage-induced deformation and related limit state analysis of levees." *International Journal of Geomechanics* 14(2):302–312.

Khilar, K., S. Fogler, and D. Gray. 1985. "Model for piping-plugging in earthen structures." *Journal of Geotechnical Engineering* 111(7):833–845.

Kleber-Lerchbaumer, U. 2012. "German levee regulations with regard to vegetation theory and practice." Presentation to Levee Vegetation Research Symposium 2012, August 28–30, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Kleber-Lerchbaumer_Presentation.pdf. Accessed August 20, 2013.

Knutson, M., and J. Fealko. 2014. *Pacific Northwest Region Resource and Technical Services—Large Woody Material Risk Based Design Guidelines*. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Region, Boise, Idaho.

Koeser, A. K., G. Hasing, D. McLean, and R. Northrop. 2013. *Tree Risk Assessment Methods: A Comparison of Three Common Evaluation Forms.* University of Florida IFAS Extension Service, Gainesville, Florida.

Kokutse, N., T. Fourcaud, K. Kokou, K. Neglo, and P. Lac. 2006. "3D Numerical modelling and analysis of the influence of forest structure on hill slopes stability." Pages 561–567 in H. Marui, T. Marutani, N. Watanabe, et al. (eds.), *Disaster Mitigation of Debris Flows, Slope Failures and Landslides: Proceedings of the INTERPRAEVENT International Symposium,* September 25–27, 2006, Niigata, Japan. Universal Academy Press, Tokyo, Japan.

Lammeranner, W. 2012. "The impact of woody vegetation on levees—Research experiences from Austria." Presentation to Levee Vegetation Research Symposium 2012, August 28–30, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Lammeranner_Presentation.pdf. Accessed February 11, 2014.

Lammeranner, W., M. Meixner, and F. Florineth. 2007a. "The effect of woody plants on dikes and levees: Design and construction of a model dike." *Geophysical Research Abstracts* 9, 06227.

Lammeranner, W., H. Meixner, and F. Florineth. 2007b. "Woody structures on dams and levees: A contradiction?" In Ernst & Sohn Special, 1 Department Congress Engineering and Natural Hazards, Wiley Architecture and Technical Sciences, Berlin, 1 Department Congress Engineering and Natural Hazards, 10–11th May 2007.

Lammeranner, W., H. Meixner, and F. Florineth. 2008. "Soil bioengineering techniques on heavily compacted soils: Experiences from a test site." *Geophysical Research Abstracts* 10.

Lammeranner, W., F. Florineth, and H. Meixner. 2009a. "The impact of different bioengineering techniques on the surface erosion of levees." *Geophysical Research Abstracts* 11.

Lammeranner, W., H. Meixner, and F. Florineth. 2009b. "The influence of woody plants on the seepage of flood protection levees: Experiences from a test site." *Geophysical Research Abstracts* 11.

Le, H. T., J. W. van der Meer, and H. J. Verhagen. 2012. “Wave overtopping simulator tests on sea dikes in Viet Nam.” In P. Lynett and J. M. Smith (eds.), *Proceedings of the 33rd International Conference on Coastal Engineering (ICCE) 2012*, Santander, Spain. American Society of Civil Engineers, Reston, Virginia.

Lee, H. L., and L. W. Mays. 1986. “Hydraulic uncertainties in flood levee capacity.” *Journal of Hydraulic Engineering* 112:928–934.

Leslie, I. N., and R. Heinse. 2013. “Characterizing soil-pipe networks with pseudo-three-dimensional resistivity tomography on forested hillslopes with restrictive horizons." *Vadose Zone Research* 12(4):1–10.

List, M. 2012. “Vegetation influence on levee operations: Inspections, flood fighting, and maintenance.” Transcript of remarks before Levee Vegetation Research Symposium 2012, August 29, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_08_29_Transcripts_Panel_2.pdf. Accessed February 14, 2014.

Lu, S. M., S. Z. Wu, and X. T. Lin. 1996. “The protection of *Spartina alternifora* on the shoreline.” *Zhejiang Hydraulic Technology* 2.

Lundstrom, T., T. Jonas, V. Stockli, and W. Ammann. 2007. “Anchorage of mature conifers: resistive turning moment, root-soil plate geometry and root growth orientation.” *Tree Physiology* 27:1217–1227.

Mao, Z., F. Bourrier, A. Stokes, and T. Fourcaud. 2014. “Three-dimensional modelling of slope stability in heterogeneous montane forest ecosystems.” *Ecological Modelling* 273:11–22.

Markle, D. G. 1979. *Levee Wave Wash Protection by Trees*. Technical Report Number HL-79-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Mays, L. W. 2011. “The role of risk analysis in water resources engineering.” *Journal of Contemporary Water Research and Education* 103(1):3.

McAnally, W. H., C. M. Wallen, P. G. Steven, S. C. Sanborn, and E. C. Maak. 2013. “Composite risk assessment for Sacramento–San Joaquin Delta levee.” *Journal of Water Resources Planning and Management*. Published online 0.1061/(ASCE)WR.1943-5452.0000362 (February 21, 2013).

McDonald, J. H. 2014. *Handbook of Biological Statistics* (3rd edition). Sparky House Publishing, Baltimore, Maryland.

McGrann, M. C., D. H. Van Vuren, and M. A. Ordenaña. 2014. “Influence of adjacent crop type on occurrence of California ground squirrels on levees in the Sacramento Valley, CA.” *Wildlife Society Bulletin* 38(1):111–115.

McLindon, G. J. 1985. “Creative spoil: Design concepts, construction techniques, and disposal of excavated materials.” *Environmental Geology and Water Sciences* 7(1–2):91–108.

Mickovski, S. B., and L. P. H. van Beek. 2006. “A decision support system for the evaluation of eco-engineering strategies for slope protection.” *Geotechnical and Geological Engineering* 24:483–498.

Mickovski, S. B., P. D. Hallett, A. G. Bengough, M. F. Bransby, M. C. R. Davies, and R. Sonnenberg. 2008. “The effect of willow roots on the shear strength of soil.” *Advances in GeoEcology* 39:247–262.

Mickovski, S. B., P. D. Hallett, M. F. Bransby, M. C. Davies, R. Sonnenberg, and A. G. Bengough. 2009. “Mechanical reinforcement of soil by willow roots: Impacts of root properties and root failure mechanism.” *Journal of the Soil Science Society of America* 73:1276–1285.

Mickovski, S. B., A. Stokes, R. V. Beek, M. Ghestem, and T. Fourcaud. 2011. “Simulation of direct shear tests on rooted and non-rooted soil using finite element analysis.” *Ecological Engineering* 37:1523–1532.

Midgley, T. L., G. A. Fox, and D. M. Heeren. 2012. “Evaluation of the bank stability and toe erosion model (BSTEM) for predicting lateral retreat on composite streambanks.” *Geomorphology* 145–146(1 April 2012):107–114.

Moreno, G., J. J. Obrador, E. Cubera, and C. Dupraz. 2005. “Fine root distribution in dehesas of central-western Spain.” *Plant and Soil* 277(1–2):153–162.

National Committee on Levee Safety. 2011. “Test your levee IQ.” *Levee Safety Connections* 1(2):1–4.

Nicoll, B. C., B. A. Gardiner, B. Rayner, and A. J. Peace. 2006. “Anchorage of coniferous trees in relation to species, soil type, and rooting depth.” *Canadian Journal of Forest Research* 36(7):1871–1883.

Nieber, J. L., and R. C. Sidle. 2010. “How do disconnected macropores in sloping soils facilitate preferential flow?” *Hydrological Processes* 24:1582–1594.

Nolan, M. F. 1984. “Vegetation on Corps of Engineers Project levees in the Sacramento–San Joaquin Valley, California.” In R. E. Warner and K. M. Hendrix (eds.), *California Riparian Systems: Ecology, Conservation, and Productive Management.* University of California Press, Berkeley, California. Available at http://ark.cdlib.org/ark:/13030/ft1c6003wp/. Accessed April 8, 2014.

Norris, J. E., and J. R. Greenwood. 2006. *Assessing the Role of Vegetation on Soil Slopes in Urban Areas.* IAEG2006 Paper No. 744.

Nunnally, N. R., F. D. Shields, and J. Hynson. 1987. "Environmental considerations for levees and floodwalls." *Environmental Management* 11(2):183–191.

[OAC] Online Archive of California. Inventory of the Records of the California Central Valleys Flood Control Association. Available at http://www.oac.cdlib.org/findaid/ark:/13030/kt0n39q713/entire_text/. Accessed May 23, 2015.

Ordenaña, M. A., D. H. Van Vuren, and J. P. Draper. 2012. "Habitat associations of California ground squirrels and Botta's pocket gophers on levees in California." *Journal of Wildlife Management* 76(8):1712–1717.

Osmundson and Associates. 1971. *Recommendations for Planting in the Beautification Program for the Alameda Creek Flood Control Project, Alameda County, California*. San Francisco, California.

Osmundson, T. 1972. *Recommendations for Environmental Enhancement, West Lewiston Levee—Snake and Clearwater Rivers, Lewiston, Idaho*. Report prepared for the U.S. Army Corps of Engineers, Walla Walla, Washington.

Osmundson, T. 1980. "Engineers Relax Controls to Get a Living Levee." *Landscape Architecture* 70(6):623–628.

Osmundson, T. F. 1973. "Breakthrough: U.S. Engineers Shift Policy with New Levee Designs." *Landscape Architecture* 63(2):118–123.

Ozeren, Y., D. G. Wren, and W. Wu. 2014. "Experimental investigation of wave attenuation through model and live vegetation." *Journal of Waterway, Port, Coastal and Ocean Engineering* 140(5), 04014019.

Pan, Y., L. Li, F. Amini, and C. Kuang. 2013. "Influence of three levee-strengthening systems on overtopping hydraulic parameters and hydraulic equivalency analysis between steady and intermittent overtopping." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 139(4):256–266.

Paul, D., and C. Slaven. 2009. "Potential failure modes of the Truckee Canal failure at Fernley, Nevada." Pages 947–967 in *Managing Our Water Retention Systems: 29th Annual United States Society on Dams Conference*, Nashville, Tennessee, April 20–24, 2009.

Peltola, H. M. 2006. "Mechanical stability of trees under static loads." *American Journal of Botany* 93(10):1501–1511.

Perlea, M., and E. Ketchum. 2011. "Impact of non-analytical factors in geotechnical risk assessment of levees." *Proceedings, GeoRisk 2011*. American Society of Civil Engineers, Reston, Virginia.

Peterson, C. J. 2012. "California Levee Vegetation Research Program windthrow project." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Peterson_Presentation.pdf. Accessed October 2, 2013.

Peterson, C. J., and V. Claassen. 2012. *Windthrow Potential on Levees: Stability of Two Species of Central Valley Trees on River Levees, Evaluated by Static Winching Tests*. California Levee Vegetation Research Program. California Department of Water Resources and Sacramento Area Flood Control Agency. Sacramento, California.

Peterson, C. J., and V. Claassen. 2013. "An evaluation of the stability of *Quercus lobata* and *Populus fremontii* on river levees using static winching tests." *International Journal of Forest Research* 86(2):201–209.

Pierson, T. C. 1983. "Soil pipes and slope stability." *Quarterly Journal of Engineering Geology* 16:1–11.

Pollen, N., and F. D. Shields. 2007. "Effects of removal of riparian vegetation on levee stability on the Sacramento River." Abstract #H31J-05, American Geophysical Union, Fall Meeting, Washington, D.C.

Pollen, N. L., and A. Simon. 2005. "Estimating the mechanical effects of riparian vegetation on streambank stability using a fiber bundle model." *Water Resources Research* 41, W07025. Available at http://dx.doi.org/10.1029/2004WR003801.

Pollen, N. L., and A. Simon. 2006. "Temporal and spatial variability in the root-reinforcement of streambanks: Accounting for geotechnical properties and soil moisture." In *Proceedings of the 8th Federal Interagency Sedimentation Conference (8thFISC), April 2–6, 2006, Reno, NV, USA.* CD-ROM.

Pollen, N. L., A. Simon, and A. Collison. 2004. "Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability." Pages 125–139 in S. J. Bennett and A. Simon (eds.), *Riparian Vegetation and Fluvial Geomorphology*. American Geophysical Union, Washington, D.C.

Pollen-Bankhead, N., A. Simon, K. Jaeger, and E. Wohl. 2009. "Destabilization of streambanks by removal of invasive species in Canyon de Chelly National Monument, Arizona." *Geomorphology* 103:363–374.

Pollen-Bankhead, N., A. Simon, and R. E. Thomas. 2013. "The reinforcement of soil by roots: Recent advances and directions for future research." Pages 107–124 in J. Shorder, D. R. Butler, and C. R. Hupp (eds.), *Treatise on Geomorphology*. Academic Press. San Diego, California.

Punyamurthula, S., and R. Millet. 2012. "Forensics and performance of California levees with vegetation." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California, August 28–30, 2012. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Punyamurthula_Presentation.pdf. Accessed January 7, 2014.

Punyamurthula, S., and C. Musto. 2014. *Influence of Vegetation on Levee Performance in California.* Manuscript for submission to the International Journal of Geoengineering Case Histories.

Ramsbotham, M. (facilitator). 2009. *American River Common Features GRR Geotechnical Expert Elicitation*. U.S. Army Corps of Engineers, Sacramento District, Sacramento, California.

Reid, L. M., and E. T. Keppeler. 2011. "Landslides after clearcut logging in a coast redwood forest." Redwood Science Symposium: Coast Redwood Forests in a Changing California, June 21–23, 2011. Santa Cruz, California.

Reid, R. L. 2005. "Is California Next?" *Civil Engineering* 75(11):39–47.

Renault, I. N.d. *Projet de Détection Électrique de Racines Vivantes: Expérimentation sur le Terrain.* Rapport de stage pour l'obtention du diplôme, d'Ingénieur de l'Ecole et Observatoire de Sciences de la Terre, de l'Université de Strasbourg, Etablissement d'accueil: Irstea Aix-en-Provence, France.

Rice, J. D., and J. M. Duncan. 2010. "Findings of case histories on the long-term performance of seepage barriers in dams." *Journal of Geotechnical and Geoenvironmental Engineering* 136(1):2–15.

Riley, A. L. 1981. *Observations and Analysis of Levee Maintenance Practices*. Division of Planning, California Department of Water Resources, Sacramento, California.

River Partners. 2013. Concern about vegetation on levees. Available at http://www.riverpartners.org/resources/riparian-ecology/veg-levees/concerns-about-veg-on-levees/. Accessed December 16, 2013.

River Partners. 2014. The flume study. Chico, California. Available at http://www.riverpartners.org/resources/riparian-ecology/veg-floodway/the-flume.html. Accessed November 7, 2014.

Robbins, B. K., J. L. Wibowo, K. S. Holden, and M. K. Corcoran. 2014. *Development of Envelope Curves for Predicting Void Dimensions from Overturned Trees.* Technical Report ERDC/GSL TR 14-27. U.S. Corps of Engineers Research and Development Center, Vicksburg, Mississippi.

Rood, K., B. Wardman, and R. Odell. 2010. *NLIP Vegetation Variance Request Tree Fall Levee Erosion Studies.* Report prepared by Northwest Hydraulic Consultants, Sacramento, California, for the Sacramento Area Flood Control Agency.

Rundnicki, M., S. J. Mitchell, and M. D. Novak. 2004. "Wind tunnel measurements of crown streamlining and drag relationships for three conifer species." *Canadian Journal of Forestry Research* 34(3):666–676.

[SAFCA] Sacramento Area Flood Control Agency. 2009. *Life Cycle Management of Levee Vegetation.* Draft report. Sacramento, California.

[SAFCA] Sacramento Area Flood Control Agency. n.d. "2007 Levee Vegetation Research Symposium." Available at http://www.safca.org/protection/Environmental_2007_Symposium.html. Accessed July 22, 2014.

Salah-Mars, S., M. W. McCann, and J. R. Benjamin. 2008. *Delta Risk Management Strategy Phase 1 Final Risk Analysis.* URS Corporation, Oakland, California.

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, Vicksburg, Mississippi.

Schwarz, M., P. Lehmann, and D. Or. 2010. "Quantifying lateral root reinforcement in steep slopes—from a bundle of roots to tree stands." *Earth Surface Processes and Landforms* 35:354–367.

Seed, R. B., A. Athanasopoulos-Zekkos, D. Cobos-Roa, J. M. Pestana, and M. Inamine. 2012. *State of the Art: U.S. Levee and Flood Protection Engineering in the Wake of Hurricane Katrina.* 2012 GeoCongress Conference: State of the Art and Practice in Geotechnical Engineering, ASCE, 25–29 March, Oakland, California. American Society of Civil Engineers, Reston, Virginia.

Serre, D., L. Peyras, R. Tourmet, and Y. Diab. 2008. "Levee performance assessment methods integrated in a GIS to support planning maintenance actions." *Journal of Infrastructure Systems* 14:201–213.

Sherard, J. L. 1986. "Hydraulic fracturing in embankment dams." *Journal of Geotechnical Engineering* 112.10 (1986):905–927.

Shields, F. D. 2007. "Role of vegetation in levee slope stability and revetment durability." Presentation to Levee Vegetation Research Symposium 2007. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/protection/Leveevegetationspeakerlist.html. Accessed December 11, 2013.

Shields, F. D., and D. H. Gray. 1992. "Effects of woody vegetation on sandy levee integrity." *Water Resources Bulletin* 917–931.

Shields, F. D., and M. R. Palermo. 1982. *Assessment of Environmental Considerations in the Design and Construction of Waterway Projects.* Technical Report E-82-8. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Shriro, M., J. Bray, N. Sitar, and D. C. Roa. 2012. "Effects of live & decomposing tree roots on levee seepage: Observations of full-scale field testing." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Shriro_Presentation_Day1.pdf. Accessed January 14, 2014.

Shriro, M., J. Lichter, and R. Evans. 2011. "Study of levee seepage and slope stability in relation to roots." In *Proceedings of the Annual Conference of the Association of State Dam Safety Officials, September 25–29, 2011, Washington, D.C.*

Shriro, M., D. C. Roa, J. D. Bray, and N. Sitar. 2014a. *Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 2—Parallel Trench Wetting Front Test, North Levee of the American River at Cal Expo Sacramento, California*. University of California, Berkeley.

Shriro, M., J. Bray, N. Sitar, and D. Cobos-Roa. 2014b. *Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance: Volume 3—Crown Trench Seepage Test, Northern Levee of Twitchell Island, Rio Vista, California.* University of California, Berkeley.

Sidle, R. C. 1992. "A theoretical model of the effects of timber harvesting on slope stability." *Water Resources Research* 28.7 (1992):1897–1910.

Sills, G. 2012. "Vegetation influence on levee operations: Inspections, flood fighting, and maintenance." Transcript of remarks before Levee Vegetation Research Symposium 2012. August 29, 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_08_29_Transcripts_Panel_2.pdf. Accessed February 13, 2014.

Sills, G. L. 2007. "A review of Corps of Engineers levee seepage practices and proposed future changes." *Proceedings of the 2007 Infrastructure Conference,* U.S. Army Corps of Engineers.

Simon, A., and N. Pollen-Bankhead. 2012. "Interactions between riparian vegetation and levee and bank stability." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, CA. Available at

http://www.safca.org/symposium_2012_documents/2012_Symposium_Simon_Presentation.pdf. Accessed March 13, 2014.

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(1):99–113.

Sips, R. J., J. Huizingalaan, A. van der Viles, R. Nagel, and B. Havers. 2013. "A case for evidence-based levee management sensor technology." *IBM Journal of Research and Development* 57(5):1–12.

Sitar, N. 2014. *Evaluation of the Incremental Risk of Levee Failure due to Effects of Woody Vegetation.* University of California, Berkeley. Proposal submitted to the California Department of Water Resources, Sacramento.

Sobhani, V. M., M. Barrett, and C. J. Peterson. 2014. "Robust prediction of treefall pit and mound sizes from tree size across 10 forest blowdowns in eastern North America." *Ecosystems* 17:837–850.

Somerville, A. 1979. "Root anchorage and root morphology of *Pinus radiata* on a range of ripping treatments." *New Zealand Journal of Forest Science* 9(1314):294–315.

Sonnenberg, R., M. F. Bransbury, A. G. Bengough, P. D. Hallett, and M. C. R. Davies. 2012. "Centrifuge modelling of soil slopes containing model plant roots." *Canadian Geotechnical Journal* 49:1–17.

Stathers, R. J., T. P. Rollerson, and S. J. Mitchell. 1994. *Windthrow Handbook for British Columbia Forests.* Working Paper 9401. British Columbia Ministry of Forestry, Victoria, B.C., Canada.

Steendam, G. J., J. W. Van Der Meer, B. Hardeman, and A. Van Hoven. 2010. "Destructive wave overtopping tests on grass covered landward slopes of dikes and transitions to berms." Pages 2704–2717 in *Proceedings of the 32nd International Conference on Coastal Engineering (ICCE) 2010,* Shanghai, China, 30 June–5 July 2010. American Society of Civil Engineers, Reston, Virginia.

Stokes, A., and C. Mattheck. 1996. "Variation of wood strength in tree roots." *Journal of Experimental Botany* 47(298):693–699.

Suddeth, R. J., J. Mount, and J. R. Lund. 2010. "Levee decisions and sustainability for the Sacramento–San Joaquin Delta." *San Francisco Estuary and Watershed Science* 8(2):1–23.

Thomas, R. E., and N. Pollen-Bankhead. 2010. "Modeling root-reinforcement with a fiber-bundle model and Monte Carlo simulation." *Ecological Engineering* 36(1):47–61.

Thornton, C., J. Meer, B. Scholl, S. Hughes, and S. Abt. 2011. "Testing levee slope resiliency at the new Colorado State University wave overtopping facility." *Proceedings, AGU Hydrology Days 2012*, Colorado State University, Fort Collins, Colorado.

Thornton, C., B. Scholl, S. Hughes, and S. Abt. 2012. "Full-scale testing of levee resiliency during wave overtopping." Pages 721–736 in *Innovative Dam and Levee Design and Construction for Sustainable Water Development: 32nd Annual United States Society on Dams Conference*, New Orleans, Louisiana, April 23–27, 2012.

Tracy, F. T., and M. Corcoran. 2012. "Numerical modeling of seepage in levees with woody vegetation." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012%20Symposium_Speaker_Tracy.pdf. Accessed April 24, 2014.

Tung, Y. K., and L. W. Mays. 1981. "Risk models for flood levee design." *Water Resources Research* 17(4):833–841.

Urata, T., M. Shibuya, A. Koizumi, H. Torita, and J. Y. Cha. 2012. "Both stem and crow mass affect tree resistance to uprooting." *Journal of Forest Research* 17(1):65–71.

Urban, J., R. Bequet, and R. Mainiero. 2011. "Assessing the applicability of the earth impedance method in situ studies of tree root systems." *Experimental Botany* 62(6):1857–1869.

[USACE] U.S. Army Corps of Engineers. 1955. *Standard Operation and Maintenance Manual for the Sacramento River Flood Control Project.* South Pacific Division, Sacramento District, Sacramento, California.

[USACE] U.S. Army Corps of Engineers. 1968. *Levee Maintenance Standards and Procedures.* Engineer Regulation 1130-2-335, Office of the Chief Engineers, Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 1969. *Design Memorandum No.5; Alameda Creek Flood Control Project, Alameda County, California—Environmental Planning*. U.S. Army Engineer San Francisco District, San Francisco, California.

[USACE] U.S. Army Corps of Engineers. 1970. *Detailed Project Report for Flood Control at Evansdale, Iowa.* U.S. Army Engineer Rock Island District, Rock Island, Illinois.

[USACE] U.S. Army Corps of Engineers. 1972. *Landscape Planting at Floodwalls, Levees and Embankment Dams.* Engineer Manual 1110-2-301, Office of the Chief Engineers, Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 1977. *Basis for Design Memorandum, Tijuana River Project, San Diego, CA.* U.S. Army Engineer Los Angeles District, Los Angeles, CA.

[USACE] U.S. Army Corps of Engineers. 1982a. *Final Supplement to the Environmental Impact Statement; Tennessee-Tombigbee Waterway, Alabama and Mississippi; Vol. 1: Environmental Impact Statement.* U.S. Army Engineer Mobile and Nashville Districts, Mobile, Alabama, and Nashville, Tennessee.

[USACE] U.S. Army Corps of Engineers. 1982b. *Phase I General Design Memorandum, Little Calumet River, Indiana.* Technical Volume D. U.S. Army Engineer Chicago District, Chicago, Illinois.

[USACE] U.S. Army Corps of Engineers. 1995a. *Introduction to Probability and Reliability Methods for Use in Geotechnical Engineering.* ETL 1110-2-547. Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 1995b. *PL 84-99, Levee Vegetation Management*. Information paper. U.S. Army Engineer Seattle District, Seattle, Washington.

[USACE] U.S. Army Corps of Engineers. 2001. *Civil Emergency Management Program: Emergency Employment of Army and Other Resources*. ER 500-1-1. Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2006. *Reliability Analysis and Risk Assessment for Seepage and Slope Stability Failure Modes for Embankment Dams*. ETL 1110-2-561. Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2007a. *Treatment of Vegetation within Local Flood-Damage Reduction Systems*. Draft final white paper, CECW-CE, Headquarters, Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2007b. "Interim vegetation guidance for control of vegetation on levees." Memorandum for major and subordinate commands and districts, CECW-HS, Headquarters, Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2009a. *USACE Vegetation Standards for Flood Reduction Infrastructure.* Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2009b. *Guidelines for Landscape Planting and Vegetation Management at Levees, Floodwalls, Embankment Dams, and Appurtenant Structures.* Engineering Technical Letter 1110-2-571, Headquarters. Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2010a. *American River Watershed Common Features Project, Natomas Basin, Sacramento and Sutter Counties, California, Post-authorization and Interim General Reevaluation Report.* Sacramento District. Sacramento, California.

[USACE] U.S. Army Corps of Engineers. 2010b. *Emergency Flood Fight Training Manual*. Washington, D.C. Available at http://www.spa.usace.army.mil/Portals/16/docs/emergencymgmt/2010-EM-Flood_Fight_Manual.pdf. Accessed October 24, 2013.

[USACE] U.S. Army Corps of Engineers. 2011. *West Sacramento Working Group Fix-in Place and Adjacent Setback Cost Comparison.* Sacramento District, Sacramento, California.

[USACE] U.S. Army Corps of Engineers. 2012. "Process for requesting a variance from vegetation standards for levees and floodwalls." *Federal Register* 77(33):9637–9650.

[USACE] U.S. Army Corps of Engineers. 2014. *Guidelines for Landscape Planting and Vegetation Management at Levees, Floodwalls, Embankment Dams, and Appurtenant Structures.* Engineering Technical Letter 1110-2-583, Headquarters. Washington, D.C.

[USACE] U.S. Army Corps of Engineers. 2015. Levee Safety Inspections. Available at http://www.usace.army.mil/Missions/CivilWorks/LeveeSafetyProgram/LeveeInspections.aspx. Accessed September 1, 2015.

[USACE] U.S. Army Corps of Engineers. n.d. National Levee Database. Available at http://nld.usace.army.mil/egis/f?p=471:1:. Accessed July 22, 2014.

U.S. Bureau of Reclamation. 2008. *Truckee Canal Breach Station 716+50 Muskrat Burrow Investigations.* Newlands Project Lahontan Basin Area Office–Nevada, Mid-Pacific Region, Geology Branch, MP-230.

[USDA] U.S. Department of Agriculture. 1974. A Guide for Design and Layout of Vegetative Wave Protection for Earth Dam Embankments." Technical Release No. 56, Design Branch, Plant Sciences Division and Engineering Division, Soil Conservation Service, Washington, D.C.

[USDA] U.S. Department of Agriculture. 2014. "A Guide for Design and Layout of Vegetative Wave Protection for Earth Dam Embankments." Technical Release No. 56, 210–VI–TR–56, Natural Resources Conservation Service, Washington, D.C.

Van Vuren, D. H., and M. A. Ordenaña. 2011. *Habitat Associations of Burrowing Mammals along Levees in the Sacramento Valley, California.* California Levee Vegetation Research Program, California Department of Water Resources and Sacramento Area Flood Control Agency. Sacramento, California.

Van Vuren, D. H., and M. A. Ordenaña. 2012a. "Factors influencing burrow length and depth of ground-dwelling squirrels." *Journal of Mammalogy* 93(5):1240–1246.

Van Vuren, D. H., and M. A. Ordenaña. 2012b. *Burrow Dimensions of Ground Squirrels, with Special Reference to the California Ground Squirrel.* California Levee Vegetation Research Program. California Department of Water Resources and Sacramento Area Flood Control Agency, Sacramento.

Van Vuren, D. H., M. C. McGrann, and M. A. Ordenaña. 2013. *Influence of Adjacent Crop Type on Occurrence of California Ground Squirrels along Levees in the Sacramento Valley,*

California. California Levee Vegetation Research Program. California Department of Water Resources and Sacramento Area Flood Control Agency, Sacramento, California.

Vanderborght, J., J. A. Huisman, J. V. D. Kruk, and H. Vereecken. 2013. "Geophysical methods for field-scale imaging of root zone properties and processes." In S. H. Anderson and J. W. Hopmans (eds.), *Soil-Water-Root Processes: Advances in Tomography and Imaging*. Madison, Wisconsin.

Vennetier, M., C. Zanetti, P. Meriaux, and B. Mary. 2014. "Tree root architecture: new insights from a comprehensive study on dikes." *Plant and Soil* 1–21.

Vergani, C., A. Chiaradia, C. Bassaneilli, and G. B. Bischetti. 2013. "Root strength and density decay after felling in a silver-fir-Norway spruce stand in the Italian Alps." *Plant and Soil* 377(1–2), 63–81.

Vogel, S. 1989. "Drag and reconfiguration of broad leaves in high winds." *Journal of Experimental Botany* 40(217):941–948.

Vollsinger, S., S, J. Mitchell, K. E. Byrne, M. D. Novak, and M. Rudnicki. 2005. "Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species." *Canadian Journal of Forest Research* 35:1238–1249.

Vorosgushyn, 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* 9:1383–1401.

Wallace, D., C. Baumer, J. Dwyer, and F. Hershey. 1994. "Levee armoring: woody biotechnical considerations for strengthening Midwest levee systems." *Proceedings, Restoration of Aquatic Ecosystems Symposium*. The Association of State Wetland Managers, St. Paul, Minnesota; USDA Forest Service, Columbia, Missouri.

Washburn, T. 2012. "Engineering design & vegetation management solutions to safely allow retention of some vegetation on levees." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Washburn_Presentation.pdf. Accessed August 20, 2013.

Whitlow, T. H., R. W. Harris, and A. T. Leiser. 1979. "Use of vegetation to reduce levee erosion in the Sacramento–San Joaquin Delta." *Annual Progress Report.* University of California, Davis, and California Department of Water Resources, Sacramento, California.

Whitlow, T. W., R. W. Harris, and A. T. Leiser. 1984. "Experimenting with levee vegetation: Some unexpected findings." Pages 558–564 in *Proceedings, California Riparian Systems.* University of California Press, Berkeley and Los Angeles, California.

Wibowo, J., and M. Corcoran. 2013. *Response to Dr. Les Harder's Comments on the Slope Stability Calculations Reported in Initial Research into the Effect of Woody Vegetation on Levees.* U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Wibowo, J., and M. K. Corcoran. 2012. "Root pullout field tests." U.S. Army Corps of Engineers. Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Robbins_Presentation.pdf. Accessed September 24, 2013.

Wibowo, J., and B. A. Robbins. 2012. *Response to December 31, 2011 Comments on ERDC Slope Stability Analyses Clarification of Load Distribution.* U.S. Army Corps of Engineers, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Wibowo, J., M. K. Corcoran, R. Kala, and D. Leavell. 2011. *Assessing Tree-Root and Soil Interaction Using Pullout Apparatus.* American Geophysical Union, Fall Meeting 2011. NASA.

Wilson, G. V., J. L. Nieber, R. C. Sidle, and G. A. Fox. 2012. "Internal erosion during soil pipeflow: State of the science for experimental and numerical analysis." *Transactions of the ASABE* 56(2):465–478.

Witmer, G. W., R. S. Moulton, and J. Swartz. 2012. "An assessment of Richardson's ground squirrel activity and potential barriers to limit access to sensitive sites at Malmstrom Air Force Base, Montana." *Proceedings of the Vertebrate Pest Conference* 25:186–189. University of California, Davis.

Wu, T. H. 2013. "Root reinforcement of soil: Review of analytical models, test results, and applications design." *Canadian Geotechnical Journal* 50:259–274.

Wu, T. H., W. P. McKinnell III, and D. N. Swanston. 1979. "Strength of tree roots and landslides on Prince of Wales Island, Alaska." *Canadian Geotechnical Journal* 16(1):19–33.

Wunder, S., B. Lehmann, and F. Nestmann. 2011. "Determination of the drag coefficients of emergent and just submerged willows." *International Journal of River Basin Management* 9.3–4(2011):231–236.

Zanetti, C. 2010. *Characterizing the Development of Woody Root Systems in Dikes.* Doctoral Dissertation, University of Provence, Aix-en-Provence Cedex, France.

Zanetti, C., M. Vennetier, P. Mériaux, and P. Royet. 2008. "Rooting of trees in earth dykes: Morphology of tree root systems on slope and risks for embankments." *Geophysical Research Abstracts* 10.

Zanetti, C., M. Vennetier, P. Mériaux, P. Royet, M. Provansal, and S. Dufour. 2009a. "Tree root systems architecture in earth dike." *Proceedings, International Symposium "Root Research and Applications,"* RootRAP, 2–4 September 2009, Boku – Vienna, Austria.

Zanetti, C., A. Weller, M. Vennetier, P. Mériaux, M. Provansal, and S. Dufour. 2009b. "Detection of buried tree root samples by electrical measurements." *Proceedings, International Symposium "Root Research and Applications,"* RootRAP, 2–4 September 2009, Boku – Vienna, Austria.

Zanetti, C., P. Mériaux, P. Royet, M. Vennetier, and M. Provansal. 2011a. "Managing woody vegetation on earth dikes: Risks assessment and management solutions." *Procedia Environmental Sciences* 9:196–200.

Zanetti, C., A. Weller, M. Vennetier, M., and P. Mériaux. 2011b. "Detection of buried tree root samples by using geoelectrical measurements: A laboratory experiment." *Plant and Soil* 339(1–2):273–283.

Zanetti, C., I. Renault, M. Vennetier, P. Mériaux, S. P. Lopes, and B. Mary. 2013. "Detection electrique de racines vivantes: modelisation et experimentation sur le terrain (Electrical detection of live root: modeling and testing)." Digues maritimes et fluviales de protection contre les submersions 2nd Colloque National June 12–14, 2013, Aix-en-Provence, France.

Zanetti, C., M. Vennetier, and P. Mériaux. 2012. "Development and decomposition of woody root systems in French earthen dikes." Presentation to Levee Vegetation Research Symposium 2012. Sacramento Area Flood Control Agency, Sacramento, California. Available at http://www.safca.org/symposium_2012_documents/2012_Symposium_Zanetti_Presentation.pdf. Accessed January 13, 2014.

Zanetti, C., M. Vennetier, P. Mériaux, and M. Provansal. 2015. "Plasticity of tree root system structure in contrasting soil materials and environmental conditions." *Plant and Soil* 387(1–2):21–35.

Zhu, J., P. A. Ingram, P. N. Benfey, and T. Elich. 2011. "From lab to field, new approaches to phenotyping root system architecture." *Current Opinion in Plant Biology* 14(3):310–317.

Zhu, S., Y. Su, and M. Sato. 2013. "Detection of tree roots and biomass estimation based on ground penetrating radar with high accuracy positioning system." Pages 1–5 in *Proceedings, IET International Radar Conference 2013*, Xi'an, China, April 14–16, 2013.

Ziemer, R. R. 1992. "Effect of logging on subsurface pipeflow and erosion: coastal northern California." Pages 187–197 in *USA Proceedings of the Chendu Symposium, July 1992, Chendu, China.* International Association of Hydrological Sciences Publication No. 209. Wallingford, U.K.

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