US Army Corps of Engineers

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-EI-5

THE EFFECTS OF VEGETATION ON THE STRUCTURAL INTEGRITY OF SANDY LEVEES

by

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August 1991

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 32374

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP — View of levee at study site showing vegetation growing on riverward side

BOTTOM — View of trench layout for root mapping

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1991

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
The Effects of Vegetation on the Structural Integrity of Sandy Levees

5. FUNDING NUMBERS
WU 32374

6. AUTHOR(S)
Donald H. Gray, Anne MacDonald, Thomas Thomann, Imogene Blatz, F. Douglas Shields, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAEWES, Environmental Laboratory,
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report REMR-EI-5

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers, Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES A report of the Environmental Impacts Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The purpose of this study was to investigate the relationship between vegetation and the structural integrity of river levees. A specific objective was to determine the distribution of roots within levee embankments, and how these roots alter soil properties of levee embankments and affect their resistance to mass wasting, surficial erosion, piping, etc. With this information, engineering criteria can be developed in the future that may allow additional (particularly woody) vegetation to remain on levee embankments where sufficient effort can be made for levee inspection. Current Corps of Engineers guidelines for levee maintenance and operation limit vegetation on the embankment to sod-forming grasses 2 to 12 in. in height to provide for structural integrity, inspectability, and unhindered flood fight access to levees.

A field study was conducted along a 6-mile reach of a sandy channel levee along the Sacramento River near Elkhorn, CA. Root concentrations and distributions were determined using the profile-wall method in which root cross

(Continued)

14. SUBJECT TERMS

Bank erosion	Piping	Slope stability
Earth reinforcement	Plant roots	Soil properties
Levee	Seepage analyses	Vegetation survey

15. NUMBER OF PAGES
145

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. (Concluded).

sections were exposed in the vertical wall of an excavated trench. Transects were excavated running both parallel and perpendicular to the crest of the levee through areas dominated by different woody plant species typical of riparian vegetation.

Lateral plant roots were restricted to, and modified, mainly the first few feet between the surface of a levee. Root area ratios did not exceed 2 percent and generally decreased approximately exponentially with depth. Most of the root biomass was concentrated in the top 2 ft. Voids and pedotubules (infilled holes or conduits) were also mapped in the vertical faces of the trenches at each site. No voids clearly attributable to plant roots were observed.

Plant roots reinforce the levee soil and increase shear strength in a measurable manner. A shear strength increase or root cohesion can be estimated from the root biomass per unit volume or alternatively from the root area ratio. Both infinite slope and circular arc stability analyses were performed on the landward and riverward slope for steady seepage and sudden drawdown conditions, respectively. These analyses showed that even low root concentrations as measured along selected transects in the sandy levee sufficed to make the slope more secure under "worst case" scenario conditions.

PREFACE

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit No. 32374, "Techniques to Reduce Environmental Impacts for REMR." The study was part of the Environmental Impacts Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The Overview Committee at HQUSACE for the REMR Research Program consists of Dr. Tony C. Liu (CECW-EG) and Mr. James E. Crews (CECW-O). Technical Monitor for the study was Mr. Crews.

The report was prepared by Dr. Donald H. Gray of the University of Michigan and by Dr. F. Douglas Shields, Jr., and Ms. Anne MacDonald of the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES). Dr. Gray was employed in the EL under the Summer Faculty Research and Engineering Program sponsored by the US Army Research Office. Technical review was provided by Dr. C. V. Klimas, EL, and Mr. Earl Edris of the WES Geotechnical Laboratory. Ms. MacDonald was responsible for all data acquisition, reduction, and analysis. Dr. Shields and Ms. MacDonald worked under the direct supervision of Dr. John J. Ingram, Chief, WREG, and Dr. P. R. Schroeder, Acting Chief, WREG, and under the general supervision of Dr. Raymond L. Montgomery, Chief, EED, and Dr. John Harrison, Chief, EL. Problem Area Leader for the Environmental Impacts Problem Area is Mr. John Cullinane, Water Supply and Waste Treatment Group (WSWTG). Program Manager for REMR is Mr. William F. McCleese, Concrete Technology Division, Structures Laboratory, WES. The report was edited by Ms. Janean Shirley of the WES Information Technology Laboratory.

Assistance with field data collection was provided by the following individuals: Ms. Imogene Blatz, San Jose State University, Ms. Leslie Tacon, University of Illinois, Chicago Circle; Mr. Wayne Sharp, WES; Mr. Thomas Thomann, University of Michigan; and Mr. Sterling Sorensen, backhoe operator, California Department of Water Resources (DWR). Their assistance was crucial to the study and is much appreciated.

A large amount of data was collected in the field study that required careful and systematic analysis. Help with this task was provided by the following: Mr. Albert Edney, Mr. James Mock, Mr. James Battle, Mr. Thomas Thomann, and Mr. Abu-El-Sha'r, all from the University of Michigan.

Site selection guidance, logistical assistance, and entry permission were provided by the following: Mr. Scott Morris, US Army Engineer District, Sacramento; Mr. Mel Schartz, California DWR; and Mr. Frank Lang, President, Reclamation District RD 1600. Their help is likewise acknowledged.

COL Larry B. Fulton, EN, was the Commander and Director of WES. Dr. Robert W. Whalin was the Technical Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic decimetres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6.894757	kilopascals

THE EFFECTS OF VEGETATION ON THE STRUCTURAL INTEGRITY OF SANDY LEVEES

PART I: INTRODUCTION

Background

1. The effect of vegetation on the structural integrity of sandy levees was investigated as part of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. REMR is a comprehensive program to investigate REMR problems associated with Civil Works Programs of the US Army Corps of Engineers. This study was conducted as part of REMR research regarding reduction of adverse environmental impacts of REMR activities.

2. Current Corps guidelines for levee maintenance and operation limit vegetation on the embankment to sod-forming grasses 2 to 12 in.* in height to provide for the structural integrity, inspectability, and unhindered flood fight access to levees (Code of Federal Regulations [CFR], Section 208.1, Title 33; US Army Corps of Engineers 1968). Sufficient vegetation to reduce surface erosion on levees is allowed.** Finally, management to retain this type of vegetation is to be carried at least 5 ft beyond the toe of the levee or any associated seepage berm. The regulations assume that maintenance will be dominated by mowing, with burning, chemical treatments (including herbicides), and grazing also allowed. Exceptions to the sod-only policy are made to allow willow (or similar) growth on riverward berms/foreshore/batture land and overbuilt levee sections to provide additional erosion control in areas of high wave or river current attack.

3. The Corps requires that non-Federal levees for which emergency repair assistance is requested be maintained in accordance with Corps guidelines for Federal project levees. Maintenance according to Corps guidelines typically is stipulated in assurance agreements between the Corps and the

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* A table of factors for converting Non-SI units of measurement to SI (metric) units is presented on page 7.

** Herbaceous vegetation which is allowed to remain substantially taller than allowable standards from year to year, and all woody vegetation, will be called "additional vegetation" throughout the body of this report. Where information is more specific, botanical classes (grasses, forbs, shrubs, trees) or species names will be used.

local sponsor to whom the levee is turned over at the end of project construction. The agreements generally cover all aspects of operations and maintenance responsibilities to be done by the local sponsor. This restriction also holds for non-Federal project levees, although the Corps has fewer means of enforcing their maintenance standards. For a more thorough review of pertinent Corps guidelines for vegetation control on levees, see Nolan (1984).

4. These standards are appropriate in the absence of data which clearly establish the relationship between the properties of vegetation on levees (size of individual plants, plant density, and rooting structure) and structural impairment of the levees. However, there are perennial maintenance costs associated with these stringent requirements, ranging from a few to tens of dollars per acre per year depending upon the physical maintenance activity (Hynson, Elmer, and Shields 1985). Clearing of brush allowed to grow on unmaintained levees is more costly, ranging in the Sacramento District from nearly $100 to over $1,000 per acre per year. The other, less tangible price exacted by limiting vegetation on levees is lost riparian habitat, particularly where the levee is located very near the river channel in an area with historically wooded riparian strips. Hynson, Elmer, and Shields (1985) summarize the wildlife issues associated with the placement and management of levees.

5. Levee embankments are designed to retain seasonal high waters within a limited overbank area. As such, they are subject to hydraulic loading for short durations, generally less than a few weeks per year. Therefore, a levee embankment usually is less intensively engineered than an earthen dam. Furthermore, due to the constraints imposed on levee alignment by flood protection considerations, foundation material may be less than ideal. Levees may fail by several means, e.g., overtopping, surface erosion, shear failure of the embankment or foundation, and piping or seepage erosion (US Army Corps of Engineers 1978). The presence of vegetation on levees can potentially influence all of these processes to varying degrees.

6. Underseepage (i.e., seepage at the base of, or through, the levee foundation) is locally a serious threat to levee integrity and must be guarded against. Underseepage and the emergence of water on the landward side is often manifested by localized upwellings or seeps that can result in sand boils. Concentrated seepage streams emerging at these boils often carry with them entrained fines. This loss of fines can result in subsidence and other distress to a levee. The occurrence and severity of boils are controlled

primarily by the relative permeability and stratigraphy of sediments on which a levee is constructed. If the boil occurs close to the toe of the levee it may undercut the toe and cause a slipout or mass stability failure of the landward slope.

7. The possibility of an embankment failure by internal erosion as a result of through-seepage is also a major concern in the case of earth dams and levees. The problem is exacerbated under long-term hydraulic loading when the phreatic surface can eventually reach the landward face of an embankment unless intercepted by internal drains. Through-seepage can also result in the formation of pipes or conduits which lead to a washout or piping failure, particularly if dispersive clays are present. Pre-existing macropores (cracks, fissures, etc.) appear to be a necessary precondition for the initiation and propagation of a washout failure involving clay fines (American Society for Testing and Materials (ASTM) 1977). Cracks or macropores can be formed in earth dams and levees by a variety of causes quite unrelated to faunal (burrowing) and floral (rooting) activity. These causes include differential settlement and internal stress redistribution. The latter produces surfaces on which little or no normal compressive stress acts. These surfaces become the loci for hydraulic fractures which can occur under very low hydraulic gradients (Sherard 1986).

Purpose

8. The purpose of this study was to investigate the relationship between vegetation and the structural integrity of river levees. A specific objective was to determine the distribution of roots within levee embankments, and how these roots alter soil properties and affect resistance to mass wasting, surficial erosion, piping, etc. of levee embankments. With this information, engineering criteria can be developed in the future which may allow additional (particularly woody) vegetation to remain on levee embankments where sufficient effort can be made for levee inspection.

9. A second objective, therefore, was to provide a summary of findings that could serve as a basis for eventual development of vegetation management guidelines that would allow maximum vegetation cover and biomass without compromising the structural integrity of levees. As the study progressed, it became apparent that the development of study methods to address these

questions was itself a fundamental objective as well. Accordingly, this study serves as a guide to future studies of this type.

Scope

10. A field investigation of a levee along the Sacramento River in northern California was conducted. Data acquired in the field include aboveground plant cover and the distribution of associated roots, and selected geotechnical properties of the levee embankment (dry bulk density, gross particle size distribution, and in situ shear strength). Permeability tests of levee sediments reconstituted to the same field density were made in the laboratory.

11. These data were used in two primary analyses. First, slope stability of a design levee embankment along the Sacramento River was analyzed for both steady-state seepage and rapid drawdown conditions using representative values of root density, soil strength properties, and permeability. Next, gross seepage and hydraulic head distributions through a representative cross section were analyzed assuming a permeable base, the phreatic surface intersecting the levee toe for steady seepage, and a skin or surface layer of variable permeability to account for the possible effect of vegetation. Seepage analysis was repeated for an approximate transient state as well. Unfortunately, neither of these two-dimensional type seepage analyses can actually predict piping potential. A transient, three-dimensional (3-D) analysis is necessary to obtain point measurements of hydraulic head and exit seepage velocity required to determine whether seepage forces are high enough to initiate piping or trigger seepage erosion. This will be the focus of future research on this topic.

12. This study has not attempted to resolve the issue of vegetation and levee inspectability. Corps project levees are to be inspected twice annually, before and after seasonal high water. The most common means of inspection is to visually observe the levee embankment for signs of piping, sloughing, surface erosion, and animal burrowing while driving the levee crown road. Such a rapid assessment of the levee surface demands that visibility on the embankment be very good; this, in turn, suggests that the vegetation cover be the minimum necessary to reduce surface erosion, i.e., short grass. However, the cost, level, and means of inspection are human resource issues, rather than technical issues. It is not known at present how much additional

inspection effort might be needed with a specified level of additional vegetation to achieve comparable results. The issue of levee inspectability and techniques to facilitate inspection, e.g., careful selection and placement of vegetation, are addressed elsewhere (California Reclamation Board 1967, 1982). Finally, local sponsors may decide that this expense is reasonable for a more aesthetically or biologically valuable levee.

13. Fundamentally, then, the issues of inspectability and ease of flood fighting are separable from geotechnical considerations in determining the extent to which vegetation in excess of current standards should be allowed to grow on a levee. However, if geotechnical considerations do not warrant allowing additional vegetation in a given situation, these human resource issues become moot.

PART II: INFORMATION REVIEW

Levee Vegetation Guidelines and Regulations

USACE regulations and standards

14. The Code of Federal Regulations (US Army Corps of Engineers 1967) contains basic regulations governing the ope. ion and maintenance of local flood protection works. With regard to vegetation, these regulations require that measures be taken to promote the growth of sod, exterminate burrowing animals, and provide for routine mowing of grass and weeds, and removal of wild growth and drift deposits. The Corps has several ancillary regulations which further address vegetation and the operation and maintenance of levees. Pertinent standards (US Army Corps of Engineers 1968) are excerpted below:

> *Maintenance Standards*
>
> *The levees will be maintained as necessary to insure serviceability against floods at all times. Standards for accomplishing the foregoing are as follows:*
>
> *A good growth of sod will be maintained where feasible with grass height from 2 inches to 12 inches, substantially free of weeds.*
>
> *All brush, trees, or other undesirable wild growth will be removed from the levee embankment. Vegetation specifically planted for aesthetics or recreation purposes may remain.*

15. Corps guidance for plantings on levees for aesthetic or environmental purposes is contained in a separate manual (US Army Corps of Engineers 1972). The guidance is to keep the basic levee structure free of roots and to provide a buffer zone of at least 3 ft (1 m) between the deepest expected penetration of plant roots and the face of the basic levee structure. If trees and shrubs are desired on a levee, the levee section must be overbuilt to accommodate the plant roots as depicted schematically in Figure 1. Alternatively, the woody vegetation may be placed in concrete tubs or planters whose purpose is to limit and confine root penetration.

California Department of Water Resources Reclamation Board guidelines

16. Concern about the environmental impacts of removing or stripping levee vegetation in the San Joaquin-Sacramento delta region spurred efforts by both the California Department of Water Resources and the Reclamation Board to seek alternative levee maintenance standards. This effort was directed at

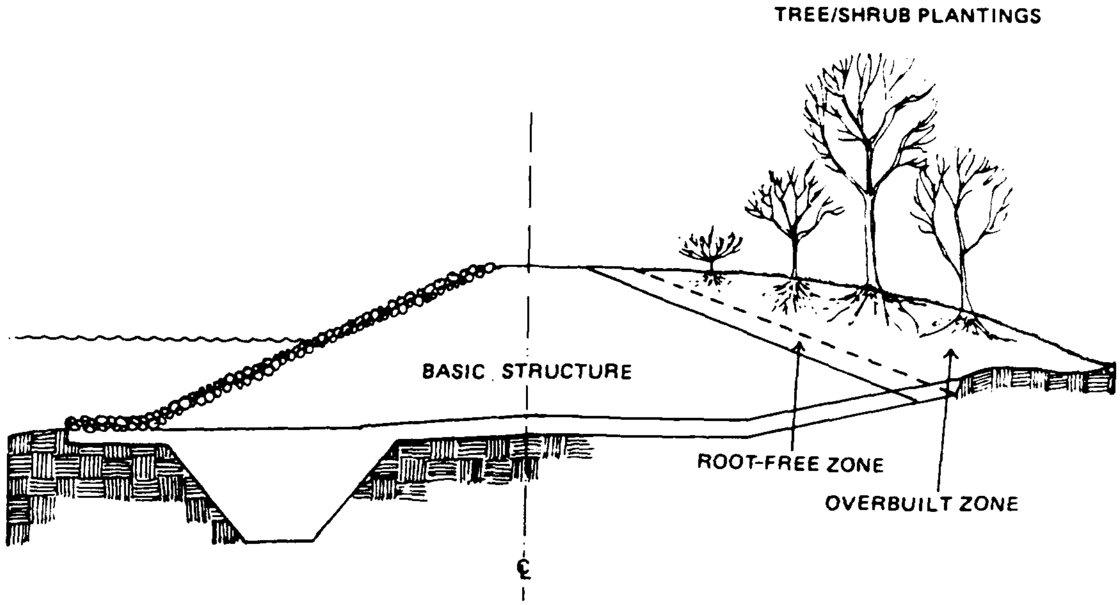


Figure 1. Cross section of an overbuilt levee

evaluating and finding feasible means to plant/retain a controlled vegetative cover for wildlife, recreation, scenic, and aesthetic purposes.

17. Results of a 5-year study to test alternative methods of levee maintenance were published in a Pilot Levee Maintenance Study (Davis, Ito, and Zwanch 1967). The study concluded that native riparian as well as other plant species could be maintained and propagated compatibly with the flood control function. Coincidental with the Pilot Levee Maintenance Study, the California Reclamation Board released a guide for encroaching vegetation on project levees (California Reclamation Board 1967) which was adopted by the Sacramento District. The guide recommended that vegetation be maintained in a controlled manner to ensure that it does not compromise levee integrity or interfere with levee inspection, maintenance, operation, or flood-fight activities. The guide required that the levee be oversized in order to provide for a root zone. The guide also specified minimum spacing intervals for trees and shrubs in order not to hinder inspection during low-flow and flood periods. Furthermore, the guide listed acceptable and unacceptable species of trees and shrubs--from the viewpoint of growth character, impairment of inspection and maintenance, and potential hindrance during flood-fighting activities. In recent years vegetation maintenance standards have been promulgated by the State of California that are more tolerant than current Corps guidelines (California Reclamation Board 1982). These State maintenance objectives and vegetation characteristics for levee maintenance zones are listed in Table 1.

Table 1

Maintenance Objectives and Vegetation Characteristics for Levee Vegetation Management Zones (California Reclamation Board 1982)

Zone	Maintenance Objectives	Vegetation Characteristics
A Ten-foot maintenance access	In areas where lands within 10 ft of the levee toe are used for levee maintenance, access for maintenance equipment must be kept open.	Low-growing grasses or ground covers which can tolerate but not impede periodic vehicle passage are desired.
B Landside slope	The integrity of the landside slope is critical during seasonal high water since it is the last line of defense against flooding of adjacent property. It is also the slope which remains visible during high water and provides opportunities for early detection of leaks, seeps, or boils. The vegetation on the landside of levees should be selectively managed to maximize its soil-binding rootmass, while providing for visibility. This will maximize both the stability of the slope as well as its visibility in case of a flood fight.	Perennial plant species with long-lived, extensive root systems adept at binding soil particles and inhibiting erosion are desired. "Cool season" species which develop extensive root systems with the onset of fall rains but whose top growth remains low until early spring meet the maintenance objectives. Clusters of taller growing shrubs or trees which meet requirements set forth in the Reclamation Board's Guide for Vegetation on Project Levees can also be desirable.
C Crown roadway and shoulders	Crown roadways are usually surfaced with gravel, although asphalt is sometimes used. Vegetation is considered undesirable when it creates automobile catalytic converter fire hazards, breaks up paved surfaces, makes gravel recovery or blading difficult, or physically prevents access or passage on the road surface.	It is desirable to keep crown roadways cleared of most vegetation. Plant populations can be tolerated if they do not impede road maintenance or vehicle movement at any time of the year.

European practice

18. In European practice, vegetation is promoted as a means of stabilizing streambanks and levee slopes. In Bavaria, West Germany, a common design practice is to construct widely spaced, vegetated levees as shown in Figure 2. A mixture of plants, including reeds, grasses, and trees, is used with riprap and other standard engineering control measures to retard erosion (Keller and Brookes 1984).

Survey of Corps District Practice

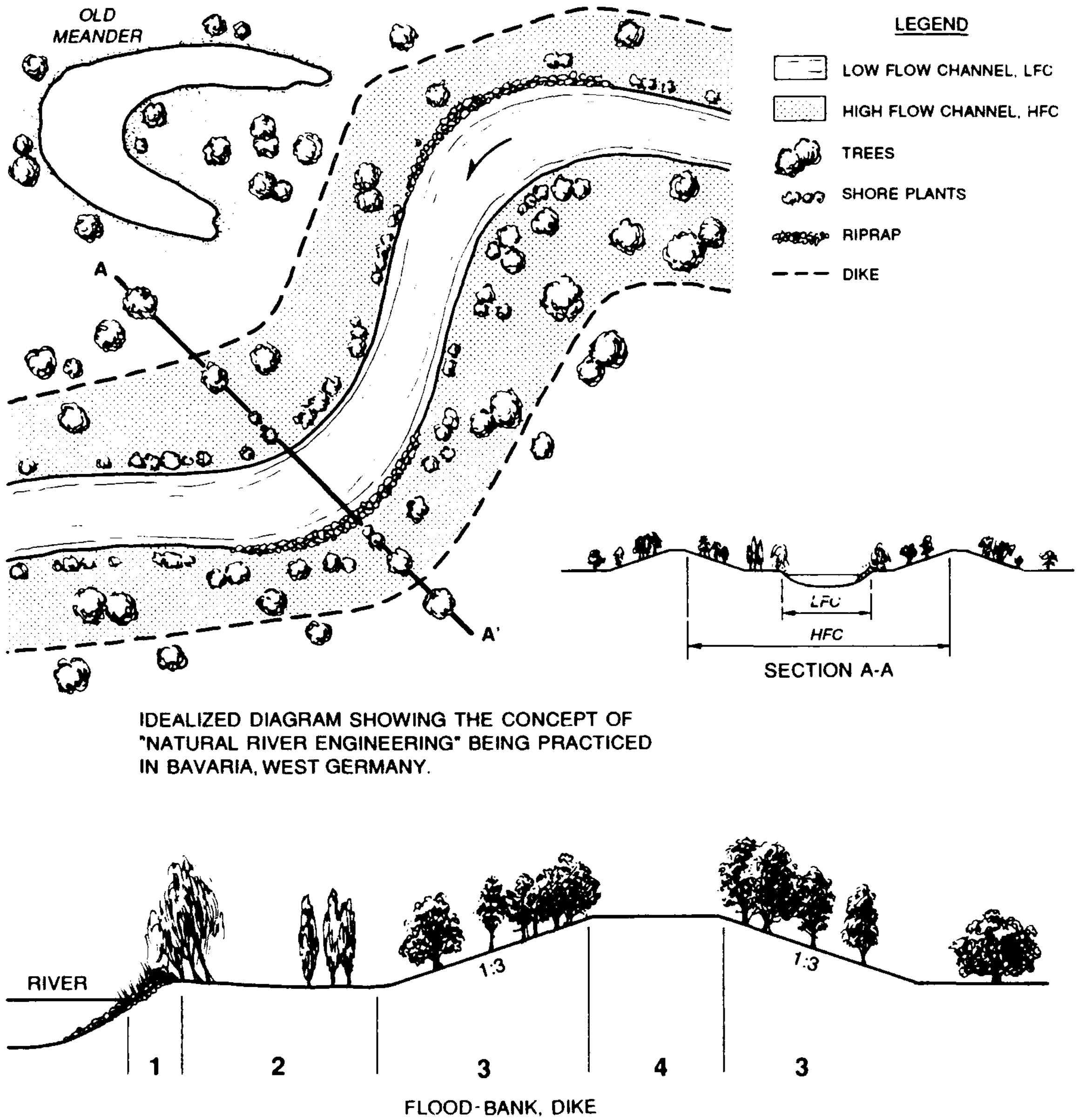
Scope of survey

19. Variances and differences in vegetation management practice exist between Corps Districts in spite of national guidelines. These differences are driven by such factors as levee types, climate, money available for inspection, and local environmental pressures. A limited study of Corps District practice was undertaken to obtain some idea of (a) major vegetation maintenance issues or problems, and (b) reasons for differences in response to these issues. The information was derived largely from site visits and interviews with District personnel.

Seattle District

20. The Seattle District has adopted minimum maintenance standards for levees in their jurisdiction that differ from most other Corps Districts. The standards explicitly address concerns about levee structural integrity while including measures which consider the impact of levees on fish and wildlife. The maintenance standards include variable standards for vegetation on levees depending upon position along the river channel as depicted in Figure 3. More extensive vegetation is allowed on riverward levee slopes located on convex bends or in straight reaches on gentle bends. The standards limit tree and shrub size to a main stem diameter of 2 in. or less. No trees or shrubs are allowed on the landward slopes or crowns. Undesirable growth that hinders inspection (e.g., blackberries and wild roses) must be removed annually.

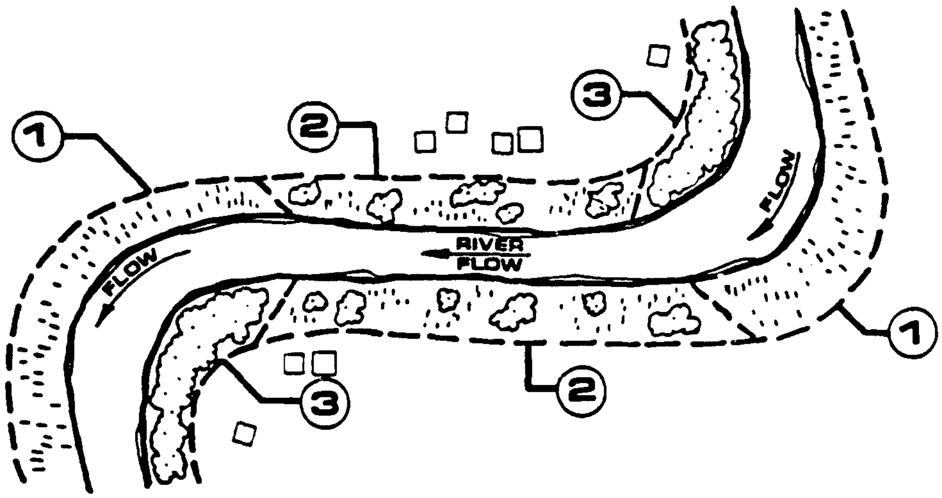
21. The variance was approved by the North Pacific Division on the basis of the unique circumstances of levee project settings along the Puyallup River near Tacoma, WA. The variance was part of a local sponsor agreement between the Corps and the Puyallup Indian Tribe. The Tribe made retention of vegetation on the embankment a condition of construction. Since the levee is maintained by the Corps, it was felt that all maintenance could be done in a



1. SHORE PLANTS; REEDS, LARGE SEDGES, ETC. PLANTED IN RIPRAP.
2. TREES (NEAR WATER TABLE) POPULAR, ALDER, WILLOW, ETC.
3. TREES (HIGHER, LESS WET SITES) OAK, MAPLE, ASH, ETC.
4. GRASS

Figure 2. Use of vegetation on flood dikes in Bavaria, West Germany (after Keller and Brookes 1984)

MANAGEMENT OF LEVEE VEGETATION



(1) Areas of HIGH potential damage, such as the outside of river bends, historically flooded areas, or levees adjacent to residences and critical use facilities should be cleared of trees and brush which could obstruct access for inspection and repair. In these levee sections, only grass and small forbs would be permitted.

(2) Areas of INTERMEDIATE damage potential such as relatively level, straight reaches and gentle bends could be selectively cleared, leaving clumps or strips of vegetation while allowing unimpeded access for inspection and repair. The type, amount and distribution of this vegetation would be carefully coordinated with the Corps of Engineers to insure levee integrity.

(3) Areas of LOW potential damage, i.e., the inside portion of river bends, levees which are seldom damaged or which protect large areas of undeveloped or relatively low value land could be maintained in a manner which would leave most levee vegetation intact, removing only that vegetation which could constitute a threat to the levee or impede levee accessibility.

Figure 3. Seattle District guidelines for management of vegetation on Puyallup River levees

timely fashion, and that there was therefore a much reduced risk of levee failure as a result of excessive vegetation growth.

Vicksburg District

22. The Vicksburg District has project levees on the Ouachita, White, Red, Mississippi, Yazoo, and Pearl Rivers. Project levees are composed primarily of fine-grained soils--silts and silty clays. Underseepage appears to be the main problem of concern. None of the project levees are overbuilt, although seepage berms are common. District personnel that were interviewed could recall no levee failures directly attributable to vegetation; however,

boils had been observed around trees growing hundreds of feet landward of levees.

23. Vegetation management on project levees consists typically of mowing, herbicides, and burning, in that order. The Corps encourages growth of Bermuda rather than Johnson grass on these levees. Few problems with vegetation maintenance on berms and embankments were reported except on the Red River, which was taken over from the New Orleans District about 1983. A review of District files suggests that most vegetation problems on the Red River levees are caused by (a) overhanging limbs from trees at the toe; (b) encroachment of vegetation on levee toes; and (c) woody vegetation growing along fencerows.

24. Different conditions and problems prevail in the case of nonproject levees. Unlike the local, engineered project levees, these levees are very sandy. The main deficiencies with non-project levees arise from overgrown vegetation conditions, insufficient freeboard caused by post-construction settling, and bank erosion, including some caving. Inspection of these levees is less frequent and less thorough.

Potential Impacts of Vegetation on Levee Structural Stability

General considerations

25. The benefits and detriments, respectively, of vegetation on embankment slopes and levees have been discussed in a number of reports, articles, and books (Nolan 1984; Greenway 1987; Tschantz and Weaver 1988; Carter and Anderson 1984; Gray and Leiser 1982). The role of vegetation has been considered with regard to a variety of issues, which include:

a. Structural stability.

b. Inspectability.

c. Flood fighting.

d. Recreation and wildlife.

e. Agricultural impact.

f. Channel conveyance.

g. Burrowing animals.

26. Of necessity this report and review are restricted primarily to one of these issues alone; namely, the influence of vegetation on structural stability and integrity. Admittedly, there are linkages between these issues. For example, to the extent that vegetation actually hinders inspection and the

ability to detect cracks, burrow holes, slumps, scour pockets, boils, and other defects in a levee it indirectly affects structural stability as well. Likewise, to the extent that vegetation attracts, or conversely discourages, burrowing animals it also affects structural stability--particularly with regard to the danger of piping and internal erosion. Voids and tunnels clearly attributable to burrowing animals were mapped during the field investigation which is the main subject of this report. The linkage between vegetation, burrowing animals, and structural stability is direct and significant enough, therefore, to merit inclusion both in a literature review and later discussion in the report.

27. The structural stability of a levee can be affected or compromised by several processes in which vegetation plays a potential role, namely:

a. Mass stability (slipouts or slides).

b. Surficial (rainfall) erosion.

c. Current/scour erosion.

d. Piping or internal erosion.

Each of these processes and the role/influence of vegetation will be reviewed briefly.

28. Unfortunately, indictments reported in the technical literature against vegetation, particularly woody plants, are often general and unspecific in nature. It is difficult, therefore, to conclude in what way and how vegetation adversely affected stability. The opinions of professional engineers (Nolan 1984) regarding the undesirability of significant vegetation on levees is characteristic in this regard. Tschantz and Weaver (1988) published a highly negative report with regard to the presence of vegetation on earthen embankment dams. Conclusions in the report were based mainly on an opinion survey of state dam safety officials. The literature on beneficial effects of vegetation on slope stability is dismissed out of hand in this report with a single sentence... "However, some people do not agree that the beneficial effects of trees on hill slopes are transferable to earth dams." Questionable cause and effect relationships have also been cited occasionally as the basis for indicting vegetation. A good example is the discovery of tree roots exposed in a breached or failed section of a dam (Shaw 1978; Tschantz and Weaver 1988).

29. The lack of specificity and carefully documented field evidence demonstrating harmful effects of levee vegetation on structural stability have been alluded to by Carter and Anderson (1984). These authors note that causes

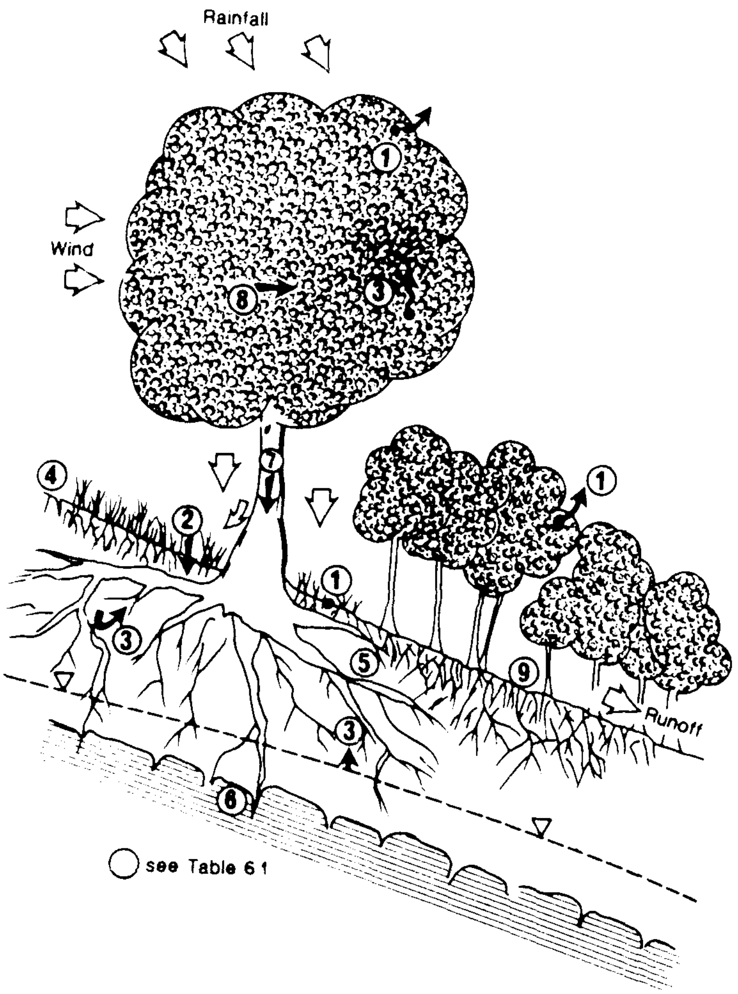
of levee failure are difficult to document and they claim that no levee failure in the Central Valley region has been attributable directly to the existence of riparian vegetation on unrevetted levee slopes. However, they also caution that vegetation which hinders a local maintaining agency in the performance of adequate inspection and maintenance increases the risk of failure. In this regard, the Pilot Levee Maintenance Study (Davis, Ito, and Zwanch 1967) developed some preliminary data and information which suggested that native and other vegetation could be maintained compatibly with flood control functions.

Vegetation and mass stability

30. Slopes fail by movement along a critical surface when the shear stress exceeds the available shear strength along the surface. A mass stability failure commonly consists of shallow, largely planar surface sliding in sandy soils or along a deeper seated, rotational failure surface which tends to occur in cohesive soils. Mass stability is strongly influenced by pore water pressures. Seepage patterns and the location of the phreatic surface affect the landside slope of a levee or earth dam, whereas sudden drawdown conditions, e.g., quickly receding flood levels, affect the stability of the riverward slope.

31. The effects of vegetation on slope stability are best documented in the soil conservation and forest engineering literature. Greenway (1987) has provided a good summary of the hydromechanical influences of vegetation as related to mass stability. These influences are depicted schematically in Figure 4 and tabulated according to whether they exert a beneficial or adverse effect. The most obvious way in which woody vegetation enhances mass stability is via root reinforcement. Extensive laboratory studies (Gray and Ohashi 1983; Gray and Maher 1989) on fiber-reinforced sands indicate that small amounts of fiber can provide substantial increases in shear strength. These findings have been corroborated by field tests on root-permeated soils (Endo and Tsuruta 1969; Ziemer 1981; Riestenberg and Sovonick-Dunford 1983).

32. Soil buttressing and arching action associated with roots and the stems/trunks of woody vegetation are also important components of slope stabilization. In addition, evapotranspiration by vegetation can reduce pore water pressures within the soil mantle on natural slopes, promoting stability (Brenner 1973). The levee environment, which can experience saturation and rapid drawdown, and in which groundwater seeps nearly horizontally across the



Hydrological Mechanisms		*Influence*
1	Foliage intercepts rainfall, causing absorptive and evaporative losses that reduce rainfall available for infiltration.	B
2	Roots and stems increase the roughness of the ground surface and the permeability of the soil, leading to increased infiltration capacity.	A
3	Roots extract moisture from the soil which is lost to the atmosphere via transpiration, leading to lower pore-water pressures.	B
4	Depletion of soil moisture may accentuate desiccation cracking in the soil, resulting in higher infiltration capacity.	A
Mechanical Mechanisms		
5	Roots reinforce the soil, increasing soil shear strength.	B
6	Tree roots may anchor into firm strata, providing support to the upslope soil mantle through buttressing and arching.	B
7	Weight of trees surcharges the slope, increasing normal and downhill force components.	A/B
8	Vegetation exposed to the wind transmits dynamic forces into the slope.	A
9	Roots bind soil particles at the ground surface, reducing their susceptibility to erosion.	B

Legend: A - Adverse to stability
B Beneficial to stability

Figure 4. Hydromechanical influences of vegetation on the mass stability of slopes (from Greenway 1987)

levee, presents a different case. It is not yet known whether the latter observations might apply to a levee embankment. Evapotranspiration effects will be significant, for example, only if flooding coincides with the vegetation growing season.

33. The primary detrimental influence on mass stability associated with woody vegetation appears to be the concern about external loading and the danger of overturning or uprooting in high winds or currents (Nolan 1984; Tschantz and Weaver 1988). If a large soil mass is disturbed during uprooting it could reduce the stability of a cross section depending upon a tree's position on the slope. This problem is likely to be more critical for large trees growing on relatively small dams or levees. With regard to external loading, levee embankment slopes are generally shallow enough that the main component of the overburden weight may act perpendicular to, rather than parallel to, the failure surface, thereby increasing stability. However, the location of trees on the embankment must be considered in any slope stability analysis in order to ascertain the extent to which their weight might affect the balance of forces.

Vegetation and surficial rainfall erosion

34. Surficial erosion entails the detachment and transport of individual soil particles as a result of a fluid (air or water) flowing over a soil bed boundary. Bare soils are particularly vulnerable to both wind and rainfall erosion. Rainfall erosion occurs in various forms ranging from raindrop splash to rilling and gullying.

35. Vegetation plays an extremely important role in controlling rainfall erosion. Soil losses due to rainfall erosion can be decreased a hundredfold on bare, fallow soil (US Department of Agriculture Soil Conservation Service 1978) by maintaining a dense cover of sod, grasses, or herbaceous vegetation. Regulations governing levee maintenance (US Army Corps of Engineers 1968) recognize the value of a sod cover and recommend its use whenever feasible.

Vegetation and current/scour erosion

36. Levee slopes are also susceptible to erosion by water currents during flood events. The erosive power of flowing water increases with velocity. Slope vegetation can help to reduce this type of erosion in the following manner: aboveground shoots bend over and cover the surface and/or reduce flow velocity adjacent to the soil/water interface, while belowground roots

physically hold soil particles in place. The extent to which vegetation provides these benefits depends upon the surface area of vegetation presented to the flow and the flexibility of the stems (Kouwen and Li 1980). Dense grass swards and low shrubs which extend numerous, non-rigid branches and leaves into the flow are the most effective in this regard. Uniformly rooted grasses (as opposed to tussocks) and supple, young willows have proven to be valuable for erosion protection (Parsons 1963; Seibert 1968). In large, wide-leveed rivers, this additional channel roughness will have a negligible effect on the stage of the design flood. In the case of a grassed surface, the hydraulic roughness depends upon the physical characteristics of the grass sward such as its height, stiffness and density, and its interaction with the flow. This interaction can be divided into three basic regimes (Hewlett, Boorman, and Bramley 1987) as shown schematically in Figure 5.

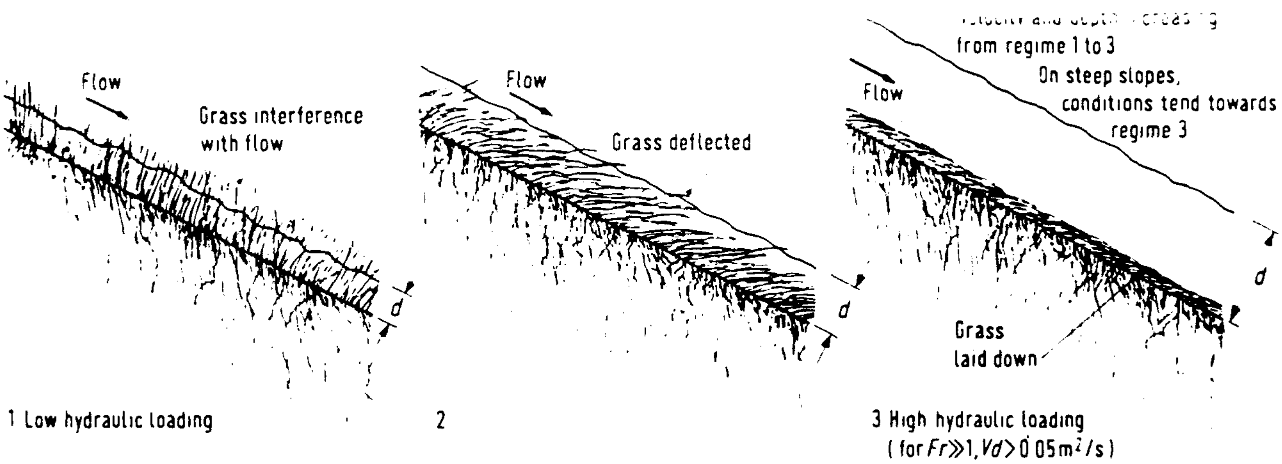


Figure 5. Effect of hydraulic loading on a grassed surface (from Hewlett, Boorman, and Bramley 1987)

In flow regime 1, the flow depth is significantly less than the height of the vegetation, which is not deflected, and the velocity at the soil surface is low due to the interference effect of the vegetation. In flow regime 2, the combined effect of increasing flow velocity and depth causes the vegetation to deflect and oscillate in the flow. In regime 3, the velocity is high enough to flatten the vegetation and a relatively smooth, stationary surface is presented to the flow. The effect of this laydown is to armor the surface and to assist in reducing local surface irregularities which might otherwise be subject to high drag forces during floods.

37. Large, isolated, rigid trees do not provide these benefits. They do not significantly reduce water velocities and instead may behave much like bridge pilings (Raudkivi and Ettema 1985). Scour around the trunk, both upstream and downstream, may be sufficient to undermine the trunk and to accelerate local bank erosion. Differential scour around large roots exposed in the streambank has been cited as a contributing cause of bank erosion (Nolan 1984); but, in undisturbed river systems with low banks and well developed bank vegetation, bank erosion is minimized because of the protection afforded by such root structures (Klingeman and Bradley 1976).

Vegetation and piping/internal erosion

38. Water seeping through an earth dam or levee can lead to a piping failure. Piping is a form of subterranean or internal erosion in which soil fines become entrained in a seepage stream. Piping can lead to washout of soil particles, removal of underlying support, and eventual collapse of an earthen structure that is subjected to hydraulic loading. Piping may pose a greater threat to stability and integrity of low, earthen embankments with gentle side slopes, e.g., levees, than mass stability failures such as slumping or rotational slides (Sherard, Decker, and Ryker 1972).

39. The phenomenon of piping in soils and earthen embankments--its causes, identification, and manifestations--has been the subject of a number of studies and symposia (ASTM 1977; Sherard, Decker, and Ryker 1972; Perry 1975; Jones 1981; and Sherard 1986). The critical role played by the presence of dispersive clays in a soil during piping is now well recognized. These clays, when present, can be easily entrained in a seepage stream, and under the right conditions, be flushed out.

40. Except in the case of internally unstable soil gradations (Kenney and Lau 1985) the consensus today is that some kind of internal fissure, crack, or macropore is required to initiate and propagate piping. Sources of quasiplanar macropores include dessication and syneresis cracks, settlement cracks, and compaction lift planes. Vegetation management itself may influence the occurrence of significant macropores. Mowing and grazing decrease macropore density because of associated compaction, while uneven, rapid surface drying in the absence of significant vegetation cover can lead to dessication cracks in an embankment (Beven and German 1982).

41. Sherard (1986), after an extensive review of available evidence, concluded that cracking in earth dams commonly occurs by hydraulic fracturing. Hydraulic fracturing is a tensile separation along an internal surface in a

soil mass or embankment on which the effective stress approaches zero; in other words, where the neutral (pore water pressure) equals the total confining stress. This hydraulic fracturing is facilitated by differential settlement and internal stress transfer in an earthen structure. Sherard also showed that in some cases a surprisingly small head differential is sufficient to "jack open" a pre-existing crack or propagate a fracture in a zone where internal stress redistribution has reduced the minor principal stress to zero or even to a tensile stress. Low, homogeneous dams without internal drains or filters appear especially vulnerable to this action following the first hydraulic loading. Channel levees fall into this category of earthen structure. One low earthen dam that Sherard inspected had developed a concentrated leak, and erosion tunnels (pipes) 225 m long under a 50:1 hydraulic gradient when the reservoir head of water acting on the upstream face of the dam was not more than 4 m. This relatively low head and gradient initiated the hydraulic fracturing.

42. Biotic activity, i.e., the actions of plant roots and burrowing animals, has provided a popular explanation for pipe development. Given the fact that the presence of some form of macropore is a prerequisite for piping in most soils, it is not surprising that biotic activity has been viewed as a likely and indeed principal cause of piping. It is, after all, a lot easier to envision relict root holes than it is to picture hydraulically induced fracture planes in an earthen embankment. Numerous levees failed along the Columbia River in 1948 when flood waters allegedly filled and spurted through channels and conduits in the levees (Cedergren 1967). Channels left by either rotted roots or burrowing animals were suspected as the cause. Root systems, or more particularly, root holes left behind by decayed roots, are frequently cited (Nolan 1981; Tschantz and Weaver 1988) as the probable cause and origin of conduits and pipes in earthen structures. Unfortunately hard evidence with regard to the penetration of roots across (or through) levees and their subsequent decay to form conduits is lacking in the published literature.

43. Much of the evidence with regard to the biotic origin and/or cause of pipes appears to be inferential or anecdotal in nature. The relative importance of animal burrows versus root holes does not seem to have been weighed nor have other causes of piping failure such as hydraulic fractures (Sherard 1986) been considered carefully.

Relationship Between Vegetation and Burrowing Activity

44. If burrow holes do indeed constitute a major threat to levee stability then it is important to ascertain to what extent vegetation either encourages or discourages such activity. The fact that the basic regulations governing the operation and maintenance of project levees (US Army Corps of Engineers 1967) explicitly call for the extermination of burrowing animals, suggests that animal burrows are a major concern. Corps levee maintenance policy (US Army Corps of Engineers 1968) requires both backfilling of animal burrows in levees and efforts to exterminate the animals by chemical and other means.

45. Hynson, Elmer, and Shields (1985) describe the types of rodents and rodent control programs associated with levees. Habitat modification is a control technique that consists of understanding the requirements of pest species and modifying vegetation types on and around a levee to produce conditions that do not meet basic food and/or cover requirements of pest species and modifying vegetation types on and around a levee to produce conditions that do not meet basic food and/or cover requirements of the species.

46. The California ground squirrel (*Spermophilus* sp.) has been the focus of much study with regard to its burrowing habits and methods to control its population (Salmon, Marsh, and Stroud 1987; Fitzgerald and Marsh 1986; Daar, Klitz, and Olkowski 1984). The California ground squirrel digs a complex burrow system in levees. Burrows average 10 cm in diameter with varying horizontal lengths of 1.5 to more than 9 m. Burrow depth varies but most are less than 1.2 m deep. Several investigators (Owings, Borchert, and Virginia 1977; Darr, Klitz, and Olkowski 1984) have noted that ground squirrels are attracted to sparsely vegetated areas where they can readily observe their surroundings for predators and communicate more easily with one another. Based on their studies in California, Darr, Klitz, and Olkowski (1984) also remarked that the traditional approach of annually burning levee slopes followed by dragging to obliterate burrow openings unwittingly improves the quality of ground squirrel habitat. In contrast, a program of deliberately maintaining certain vegetation on levee slopes may tend to discourage squirrel colonization. Fitzgerald and Marsh (1986) are doubtful about the success of this approach, however, in light of their experiment with special plantings of tall grass and broad-leafed species which actually resulted in larger squirrel populations in some grass plots. It appears from a review of the literature

on this subject that differences of opinion exist on the connection or causal relationship between vegetation and burrowing activity. Further studies are required to resolve this issue.

Root Distribution and Architecture

47. It is considerably more difficult to obtain information about the development and distribution of plant roots below ground than about stems and foliage above ground. Nevertheless, quite a lot of information has been published on this subject (Hermann 1977; Sutton 1980). Furthermore, there are well-documented techniques and methods for studying plant roots (Bohm 1979).

48. Roots can extend considerably beyond the width of the crown in some species although rooting density decreases rapidly with distance from the stem (Hermann 1977). Numerous studies have shown that most roots are found in the upper 50 cm of soil, and most root activity and mycorrhizae in the top 20 cm, depending on soil aeration and fertility (Fogel 1980; Hermann 1977). Roots have been found at depths as great as 6 m in sandy soils where aeration requirements are not as restrictive. Localized concentration of roots may occur in decaying roots, channels formed by decaying roots, and in thick litter (McGinn 1963). These observations simply underscore the fact that roots also tend to find and exploit pathways or channels of least resistance or favorable rooting environment.

49. Field methods for studying root distribution and architecture can be classified as follows:

- a. Excavation methods.
- b. Monolith methods.
- c. Auger method.
- d. Profile-wall method.
- e. Glass-wall method (rhizotron).

50. Bohm (1979) provides detailed information on each of the methods and their relative advantages and limitations. Selection of the best method depends upon the root parameter information of interest, site constraints, available labor, level of accuracy, and detail required. Root parameters commonly used to express growth and distribution are number, weight, surface, volume, diameter, length, and number of root tips.

51. The excavation method provides the clearest picture of the entire root system as it exists naturally in the ground. The length, size, shape,

orientation, and other characteristics of individual roots making up the root system can be studied directly. In addition, the interrelationship between competing root systems of other plants can be studied. On the negative side, the excavation method requires large amounts of physical labor and is very time-consuming. It also results in considerable site disturbance and does not record much about relict roots or biopores, except as they may be exposed during the excavation process.

52. The profile-wall method is probably the method most suited for studying the distribution of both woody plant roots and biopores in earthen levees. In this method, either tangential or radial trenches are dug at certain distances from a tree or along specified transects and the tips of the cut roots are mapped in one of the walls of the trench. This is done by first carefully scraping, brushing, or spraying the surface to reveal the tips of the cut roots. A gridded, acetate overlay is then placed over the vertical face or wall of the trench. Roots are mapped according to their location and size category. A different symbol can be used for each size category. The overlay technique is appropriate for investigating not only root distribution but also for determining root area ratios as a function of depth and the distribution of biopores and pedotubules.

53. The profile-wall method can be adapted for nearly all kinds of soils. Problems arise in soils of very high clay content or in very loose soils. The method requires no expensive equipment; the trench is dug by hand or with a backhoe. The combined soil and root profiles obtained by this method are good basic material for interpreting root data, especially if results for different sites are to be compared (Bohm 1979). It also permits observations and mapping of soil biopores and pedotubules.

PART III: FIELD DATA ACQUISITION

Site Selection and Description

Selection criteria

54. Site selection was governed by both study objectives and practical constraints. The main study objectives of the field work were to examine the influences of additional vegetation on levee structural stability and to develop techniques for determining the distribution of roots and biopores in a levee cross section. The initial site was selected to meet these objectives and to maximize useful information gained from the study. Inquiries about possible field study sites were directed to all USACE Divisions. Candidate sites for an initial study were narrowed down to the Sacramento District in California and the Seattle District in Washington. Time limitations and funding availability eventually limited the field study to a single area.

55. The search for a suitable site was focused in the Sacramento District because this District has severely overgrown project levees and because this condition has been an issue there since the publication of the Pilot Levee Maintenance Study (Davis, Ito, and Zwanch 1967). Selection criteria used in locating a suitable site included the following:

- a. Presence of a mixed, woody species vegetation community.
- b. Roadway access and backhoe accessibility.
- c. Availability of levee construction and channel hydrologic records.
- d. Permission and cooperation of local jurisdictions to trench and excavate.

The availability of good levee management/maintenance records should be considered as a criterion in future studies of this type because this would improve understanding of vegetation development or succession on the levee over time.

Study site location

56. Several potential study sites were investigated along the Sacramento River between Knight's Landing and Sacramento. The site ultimately selected is located on the west bank of the Sacramento River between the confluence of the Sacramento and Feather Rivers and the Interstate-5 bridge at Elkhorn, CA (see Figure 6). The study reach is approximately 6 miles long and is located in Reclamation District No. 1600. This reach was chosen because it

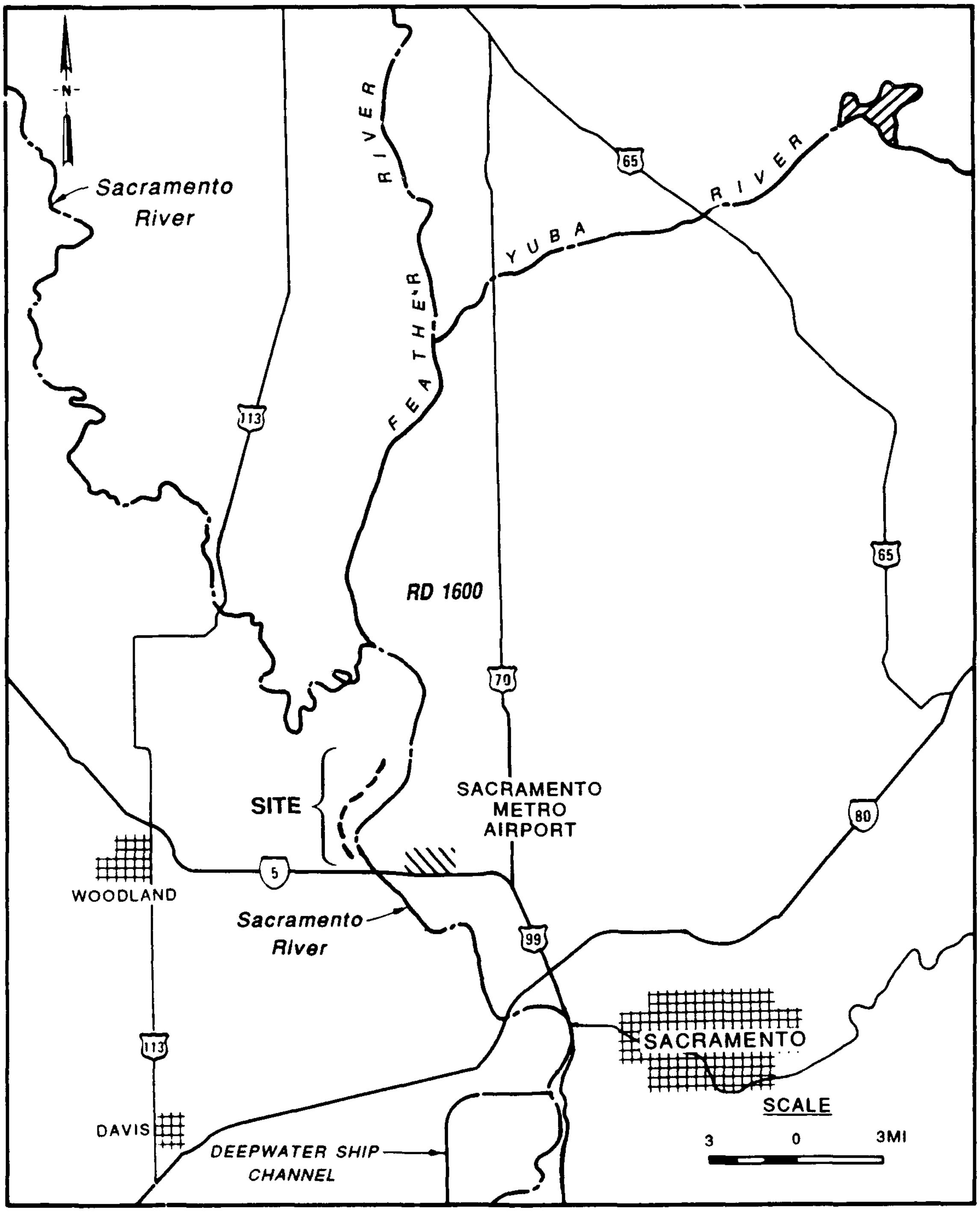


Figure 6. Study site location, Sacramento River, near Elkhorn, CA

met the selection criteria and afforded the best mix of vegetation on an active levee. The levee reach in question contained monospecific clumps of typical native and introduced riparian vegetation, some of which were objectionable from the Sacramento District maintenance point of view, and were not in compliance with levee maintenance engineering manuals (US Army Corps of Engineers 1972, 1978). The director of the local reclamation district, who was a local landowner, gave his permission for the study. Logistical support in the form of a backhoe with an operator and watertank truck was supplied by the local office of the California Department of Water Resources.

Levee characteristics

57. The levee section in question was not engineered, having been built of material dredged from the river and hydraulically deposited on the bank. The levee was constructed between 1912 and 1916 at the height of hydraulic-mining-induced flooding in the Sacramento-Feather River system. The levee consists of a low embankment or dike approximately 12 ft high. An unsurfaced road about 20 ft wide runs along the crest. Seepage is locally a problem; a filter cloth/gravel berm was recently placed along a 100-ft section of the levee on the landward toe of the levee immediately upstream of the study location. There is also a rock revetment bank protection project near the south (downstream) end of the study site.

58. The levee embankment is composed primarily of sandy soils which support mature, 30+-year-old cottonwoods and valley oaks. Black locust, shrubby willows, wild rose, and poison oak make up the balance of the woody plant community growing on the levee. Burning is used to maintain the levee vegetation at its current levels. The fire environment can significantly modify or change levee vegetation. Unfortunately, reliable information on the frequency and timing of burning was not readily available. Only limited information was gathered about the extent to which past burning practices might have altered the vegetative spectrum and other conditions, e.g., root structure and distribution, relative to that which would exist under natural succession. California ground squirrel burrows are ubiquitous in the levee. A general view of the levee illustrating some of the aforementioned features is shown in Figure 7.

59. The steeper, xeric landward slope of the levee generally faces to the west and receives not only the afternoon sun but also the force of occasional strong winds. Additionally, this face of the levee is burned annually to help prevent field fires (see Figure 7). Little grew in this harsh

Figure 7. General view of levee at study site showing vegetation growing on riverward side and burned-over slope on landward side

environment during most of the field sampling period (October through March). During March, after the advent of winter rains and warmer weather, vegetation became lush here. This proved to be the best time to identify species on the landward slope. Valley oaks are the dominant woody species here. Under the oak canopies, grasses and other ground cover, e.g., horsetails (*Equisetum*) are protected from the desiccating sun into the early summer.

60. The level crest of the levee includes a frequently travelled crest road and road shoulders. Most plants here are stunted and only hardy pioneers survive. Most of the growth on this high, dry surface occurs in the early spring when lupine (presumably hydroseeded) covers much of the area. During most of the year, storksbill (*Erodium*) blankets the area.

61. The generally east-facing riverward slope is less steep and more mesic than the landward slope and supports plant growth over a broader temporal range. Valley oaks and Fremont cottonwoods are the dominant species with storksbill totally covering most of the areas that have no tree or shrub canopy.

62. Hydraulic information for the reach of channel adjoining the levee study was calculated from flood hydrograph data measured at the Verona gaging station. Discharges of known duration from the post-Shasta Dam time series of

daily values at the Verona gage were carried upstream using HEC-2 from known stage-discharge relationships at the I-Street bridge discharge gage in downtown Sacramento. HEC-2 cross sections were located at particular study locations along the levee reach in order to estimate the total durations of hydraulic loading at various elevations and to determine the amount of freeboard during peak floods. At its lowest point the levee had less than 2 ft of freeboard during the peak of the winter 1986 floods. The stage-duration estimates were used in conjunction with transient seepage analyses, described later in the report, to determine likely frequency for development of an equilibrium or steady-state phreatic surface in the levee that would intersect the landward toe.

Trench sites

63. The distribution of roots and biopores at various locations in the levee was determined using an adaptation of the profile-wall method (Bohm 1979). This method requires the excavation of a narrow trench in order to expose and map roots, pedotubules, conduits, and other inclusions that intersect the vertical face of the trench. The trench sites were selected so that the root architecture and distribution of the principal woody species of interest growing on the levee could be mapped. Each trench site was located in an area dominated by the following woody species: live and dead valley oaks (*Quercus lobata*) willow (*Salix hindsiana*) elderberry (*Sambucus mexicana*), and black locust (*Robinia pseudoacacia*). In addition a control site consisting of herbaceous cover and low shrubs was also trenched. A total of seven sites were thus identified and selected for trenching; their location is noted on Figure 8. Site No. 1 (cottonwood) was not trenched simply because of time limitations.

Physical Data

Levee cross-section surveys

64. The geometry and dimensions of the levee were determined by field surveys. A cross section was surveyed at each trench site location starting from the landward toe, across the levee crown, to the closest proximity of the edge of the active channel. The latter was usually the top of the riverbank, although poison oak and blackberry bushes precluded this option at the willow and elderberry sites.

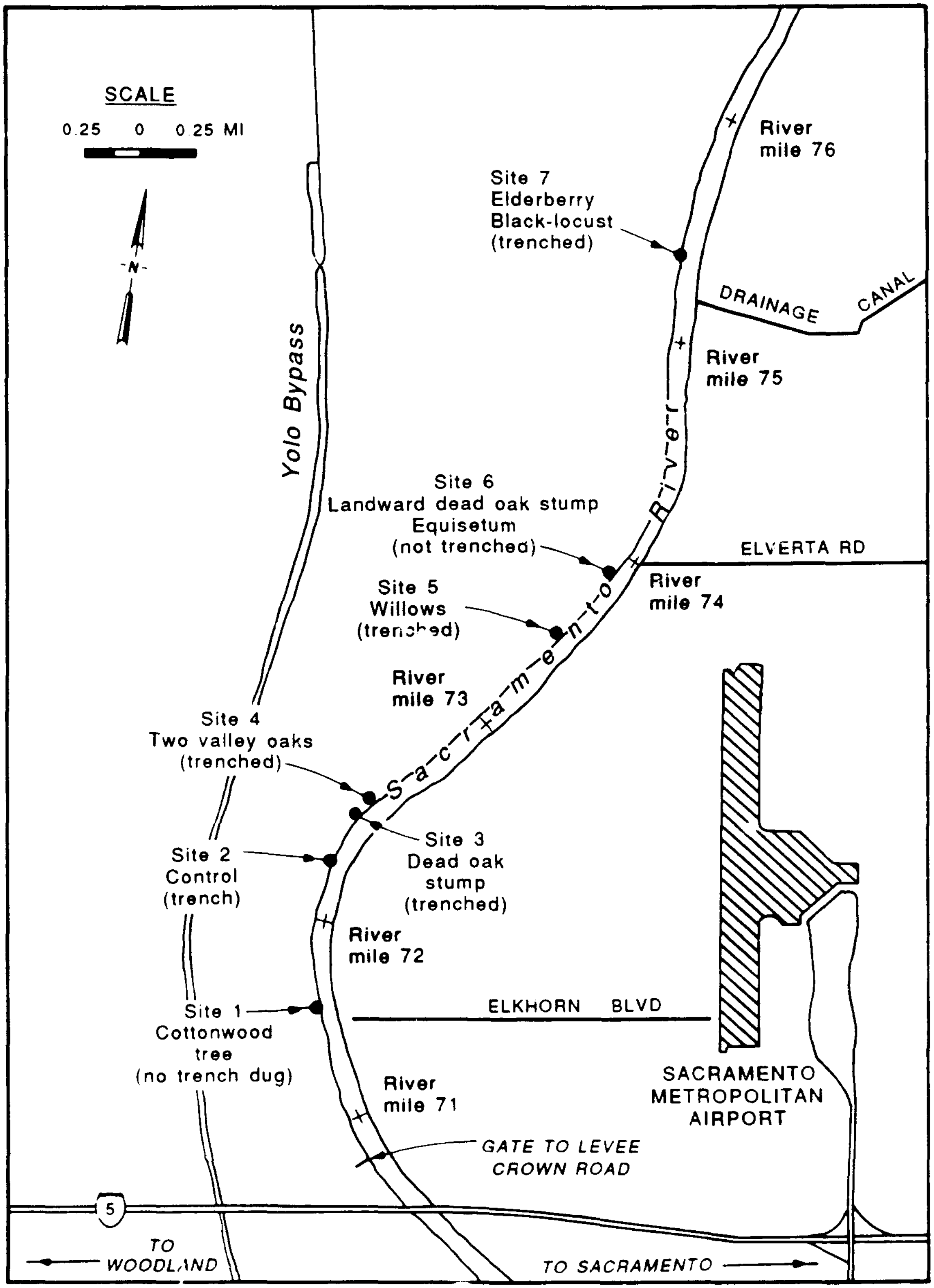


Figure 8. Location of trench sites for determination of root and biopore distribution associated with different types of vegetation

Soil information

65. Grain size analysis. Grain size analyses were conducted in order to classify and characterize the levee soils at each trench site location. Samples for grain size tests were obtained at 6-in. intervals to a depth of 4 ft using a 2-in. bucket type auger. The auger holes or borings were also used in connection with bore hole, direct shear tests. The borings were made along the axis of each trench site prior to trenching. Samples were also collected from suspected pedotubules. A pedotubule is a relict conduit or biopore that has been infilled by soil that is washed in from the surrounding area (Brewer and Sleeman 1963). In this case samples were taken from the area of the suspected pedotubule and surrounding soil as well. Differences in gradation between the two areas were interpreted as supporting evidence for a pedotubule. An example of a pedotubule that was exposed in a trench at the live oak site is shown in Figure 9.

66. Grain size distribution was determined using standard testing procedures as described in ASTM D422-58 (ASTM 1985). Most samples were predominantly coarse-grained, so that a sieve analysis alone sufficed to determine gradation.

67. Field density tests. Field densities were measured at different depths and locations along the trenches in order to determine the influence, if detectable, of plant roots on soil void ratio or porosity. Porosity is inversely proportional to dry density. The field density of soils at the trench sites was determined by means of a small tube sampler known as an Eley volumeter. The volumeter consists of a tube with a piston that is pushed into the soil a distance of approximately 3 in. The volumeter and its contents are then excavated, and a calibrated volume of soil (usually 30 cm^3) is extruded from the sampler into a sample bag. The soil is later oven-dried and weighed to determine the dry density. The dry density is determined by dividing the dry weight of solids by the extruded volume.

68. Volumeter samples were obtained from the exposed, vertical faces of the trenches as close to the bore holes used for grain size sampling and the insitu, direct shear tests. Samples were also removed from areas of suspected pedotubules. Contrasts in density between the suspected pedotubule and surrounding soil were also used as supporting evidence for the existence of a pedotubule at that location in the same manner cited previously.

69. Borehole shear tests. Effective shear strength parameters, i.e., friction ($\emptyset'$) and cohesion (c') were determined in situ using an Iowa

Figure 9. Suspected pedotubule exposed in vertical face of trench at live valley oak site (site 4) at depth of 2 ft (pedotubule appears as light-colored area with eliptical cross section in center of photograph)

borehole, direct shear device (Wineland 1975; Handy 1986). Shear strength can be determined rapidly as a function of depth with this device without the need to obtain samples. The borehole shear test consists of augering a pilot hole and then reaming to a diameter of 3 in. in order to create a borehole with smooth sides. A small pneumatic piston with serrated shearing heads at either end is then lowered down the borehole to the depth of interest. The serrated heads are next expanded out against the sides of the hole with a known normal stress. After an appropriate consolidation interval, the heads are pulled up the hole, thus creating a shearing stress. The tangential or shearing stress is recorded by means of a force platform at the surface which transfers the tensile force in the pulling rods to hydulic cells which record the shearing stress at the serrated heads in the borehole as shown schematically in Figure 10. A photograph of a borehole shear test set up at a levee site is shown in Figure 11.

70. Some difficulty with the borehole shear method is encountered in the case of very dry, cohesionless soils where the borehole tends to cave.

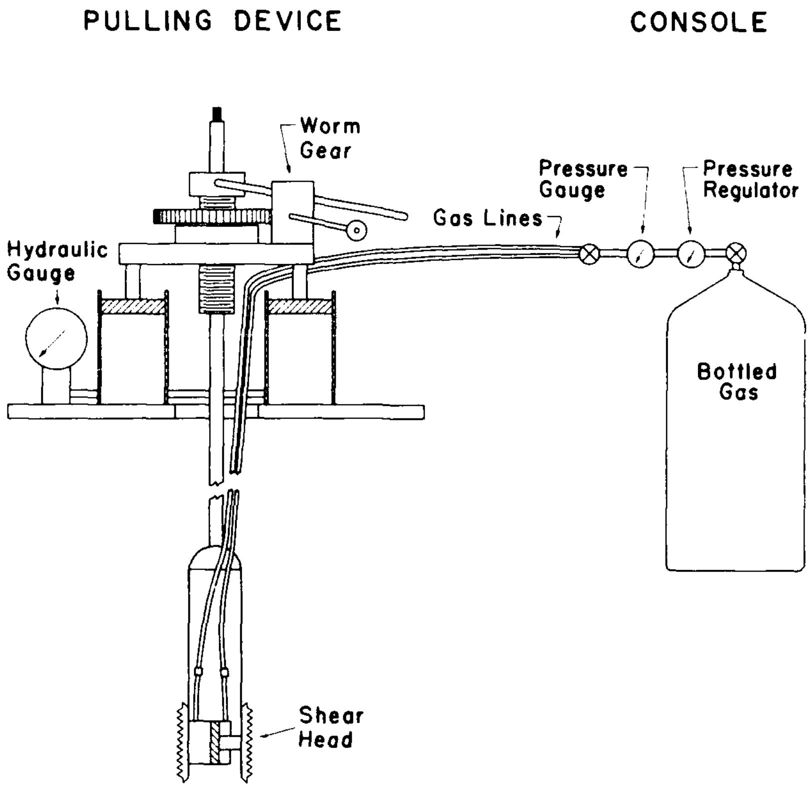


Figure 10. Schematic illustration of Iowa borehole direct shear device (*from* Wineland 1975)

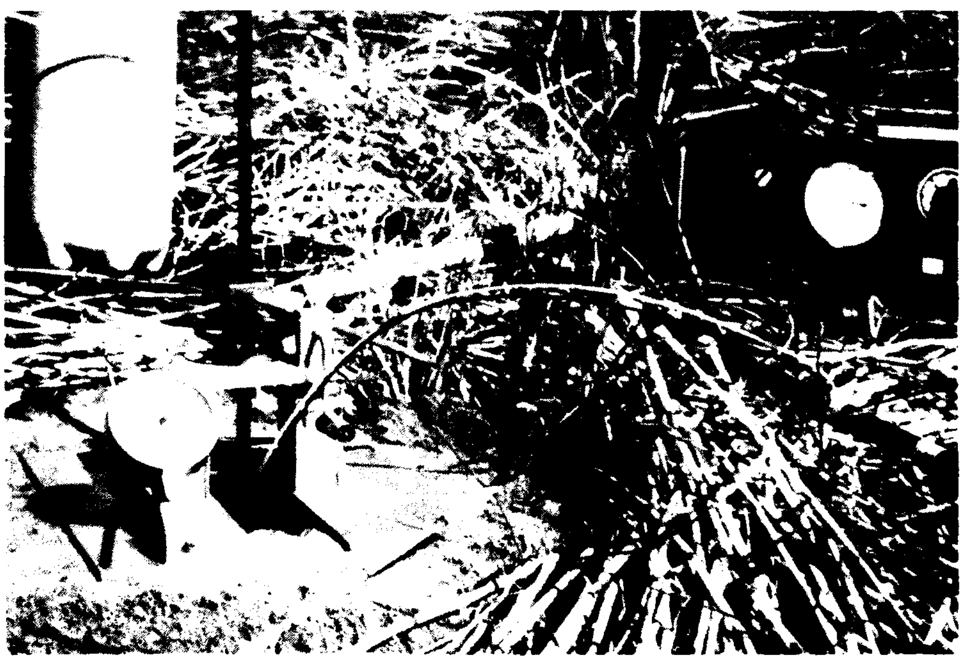


Figure 11. Iowa borehole shear test set up at levee site

This problem was circumvented at the levee site by prewetting the soil to provide sufficient capillary cohesion to prevent the soil from collapsing. This small amount of capillary or apparent cohesion vanishes below the groundwater table or when a sand dries out completely.

Botanical Data

Aboveground (vegetation inventories)

71. Transect surveys. The levee vegetation was surveyed in order to determine typical species composition, distribution, and cover in the study reach cover. In order to obtain a random sample of the vegetation along the 6-mile study section, the levee was divided into miles, starting from the gate on the levee crest road at the south end of the section. Each of the miles was divided into tenths and the tenths subdivided into fifty-three 10-ft-wide segments. The segments were oriented perpendicular to the crest road (or river) and extended from the landward toe of the levee to the riverbank edge. A random numbers table was then used to choose a mile tenth and a 10-ft segment within that tenth for a vegetation survey. A single 1-m-wide transect was then located at the south end of each selected 10-ft segment.

72. The boundaries of the 1-m transects were marked on the ground. Starting at the riverbank, the percent of each transect covered with vegetation was noted in addition to the cover fraction contributed by each genus (if it could be discerned). General categories were utilized if no identifications could be made. The vegetation was divided into three categories: trees, shrubs, and ground cover. Each category was estimated or actually drawn on the plots of the transects and later counted using graph paper. A matrix of plant genera (or general class) versus environment of the transect was plotted following the procedure described by Whitlow and Bahre (1984).

73. Trench site surveys. The trench sites were not randomly selected; instead they were located according to vegetation of interest, e.g., valley oak, willow, elderberry, etc. In general, the trenches were excavated on a line that intersected the canopy edge of the dominant species at the site. All of the live, aboveground vegetation within a 1-m strip 1 m on either side of what eventually would become the inspection face of the trench was inventoried. Measurements were made of the exact location of the plant stem or stems, the canopy cover and the height of each species of grass, forb, or shrub. This information was plotted on a graph of the area. In the case of

the valley oak and black locust canopies, notations were entered on the plot but not recorded as ground cover. The percent of total ground covered and the total cover of each species within the total cover were recorded in a tabular format.

Belowground (excavation and trench profiling)

74. In order to address the question of the amount and distribution of roots in levees, a series of trenches were excavated in the levee section at selected locations. Each trench was located in an area dominated by a different type of woody species of interest. The root density distribution with depth was mapped on two trench faces, one parallel and one perpendicular to the levee crest. The profile-wall method described by Bohm (1979) was adapted for root and bipore mapping at all the trench sites with live vegetation present. The so-called "partial excavation" method, also described by Bohm, was used at the dead valley oak site in order to gain a better idea of the root architecture as well.

75. Trenching procedure. An L-shaped trench approximately 4-ft deep was dug at each site. One arm of the trench was oriented parallel, and the other perpendicular, to the levee crest. The trench arms were usually located at the drip line or crown edge of the plant(s) of interest. In some cases the trench was positioned to pass close to the approximate center of a clump of stems.

76. Because of the loose, sandy nature of the levee soils it was necessary to water the site before excavation could proceed. Watering developed sufficient capillary cohesion in the soil to permit trenching without collapse of the vertical face of the trench. An 8,000-gal watering truck and spray hose (see Figure 12) were employed for this purpose. The live oak site required four truckloads of water before sufficient capillary cohesion developed over the entire trench site.

77. Following watering and prior to excavation, a pruning saw was run along the flagged trench face line to cut surface roots. The saw cut roots up to 8 to 10 in. below the ground line, thereby limiting disturbance to the mapping face from subsequent excavation. The trench was excavated with a backhoe; the bucket was kept approximately 6 in. away from the proposed mapping face. Care was taken not to break roots back into the face. Field crew members were on hand with pruning saws to cut any roots that were not easily

Figure 12. Watering truck and spray hose employed to wet site prior to excavation

broken by the backhoe bucket. This requirement was especially critical in the case of any large-diameter lateral roots encountered in the trench.

78. After the backhoe work, the soil along the trench sides was trimmed back to the mapping face using hand tools. A square-nosed shovel was used for rough trimming followed by smoothing with a mason's trowel. Roots were cut back to the finished face with either a pruning saw or shears. Mist spraying was employed periodically to keep the face moist and to prevent sloughing or ravelling. Hand trimming was done in two stages. The upper half of the trench was finished first, leaving a ledge on which to rest the mapping apparatus. General views of the trench layout and finishing operations prior to mapping are shown in Figures 13 and 14.

79. Mapping procedure. The roots were mapped on an acetate overlay held on a portable PVC mapping frame. The tubular frames were rectangular in shape with a mapping area 1.0 m by 0.5 m. Strings were strung across the frame on a 10-cm grid spacing. The string grid greatly facilitated keeping track of features as they were mapped and also maintaining correct placement of the mapping frame. Removable holders were placed at each end of the frame for both take-up and supply of the acetate rolls. The frames were pressed against the smoothed, vertical face of the trench, and roots plus other

Figure 13. General view of trench layout for root mapping at valley oak site

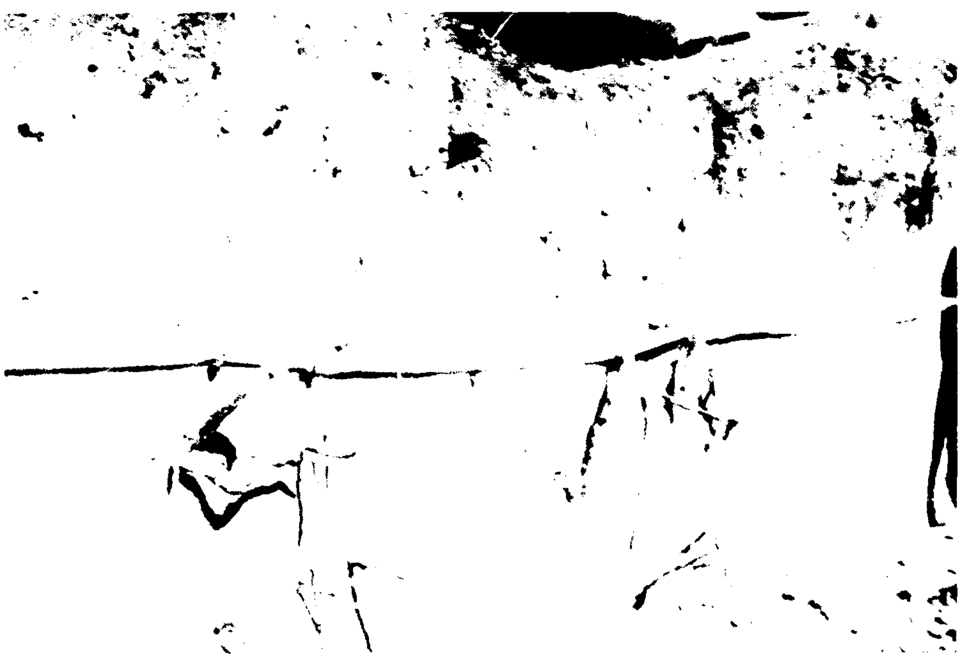


Figure 14. View of trench showing vertical mapping face and roots protruding from trench sides (burrow is visible in upper center of photo)

features mapped directly on the acetate. Mapping was done along the upper half of the trench by successively moving the frame along the ledge and advancing the acetate roll to a new position. After the upper half was mapped, the ledge at midheight was trimmed away, and the bottom half mapped in a similar fashion. Views of a mapping operation in progress are shown in Figures 15 and 16.

80. The following features were mapped on the acetate overlay:

a. Roots in the size classes < 1 mm, 1-2 mm, 2-5 mm, 5-10 mm, 10-20 mm, 20-30 mm, 30-50 mm, and > 50 mm. The actual diameter was noted or the root cross section outlined on the acetate for roots in the last category.

b. Voids or macropores with the shape and likely cause of void where obvious. Recent ground squirrel burrows were relatively easy to identify.

c. Mineral inclusions of rocks, clay clods, etc.

d. Gross stratigraphy such as different soil layers, burned layers.

81. At the conclusion of mapping, the trenches were backfilled with the excavated soil and compacted. Trench profiling was employed at all the sites of interest with the exception of the dead valley oak site. Only a stump was present here so the soil was removed on all sides in order to expose as much of the root system as possible and reveal the root structure or architecture.

Figure 15. Mapping in progress along upper half of trench face at valley oak site (mapping frame is resting on mid-height ledge)

Figure 16. Closeup view of mapping frame showing acetate sheet, take-up and supply holders, and string grid

PART IV: DATA ANALYSIS AND RESULTS

Physical Data

Levee geometry and stratigraphy

82. Channel levees along the Sacramento River typically consist of a low embankment approximately 12 ft high with a 3:1 slope on the riverward side and 2:1 slope on the landward side. An unsurfaced roadway about 20 ft wide runs along the crest of the levee.

83. Levee cross sections surveyed at each of the trench sites are shown in Figures 17 through 20. The standard levee section is superimposed on these diagrams for comparison. In general the actual cross sections closely matched the standard section. In some locations, e.g., sites 2-4, the riverward slope is less steep than the standard 3:1 slope. A relatively flat terrace of varying width separated the riverward toe of the levee from the top of the riverbank.

84. The levee in the study section was constructed primarily of sandy materials dredged from the river and hydraulically deposited on the bank. The levee soils consist primarily of medium to fine sands with little or no fines (silt or clay). Evidence from boreholes and trenches dug in the levee suggests that the finer materials that occasionally showed up tend to be located at depth, and in some cases may actually occur in the foundation as opposed to the levee itself. Nevertheless, small zones or inclusions of clay or silty clay can also be found in the structure. In some cases fissures or cracks in these clay inclusions are permeated with roots as shown in Figure 21. Roots exploit these zones, most likely because of greater water retention and availability in comparison to the surrounding, droughty sand. There was little evidence of any consistent vertical zonation or stratigraphic pattern. Stratification was evident in some locations on the riverward side where sediments had been deposited on the levee slope during overbank flows. Stratification was clearly delineated in this case by the presence of buried carbonaceous layers from previous levee burning. Examples of this stratification are shown in Figure 22.

Soil properties

85. Gradation and classification. The levee soils generally consist of fairly uniform, medium to fine sands with little or no fines (silts or clays).

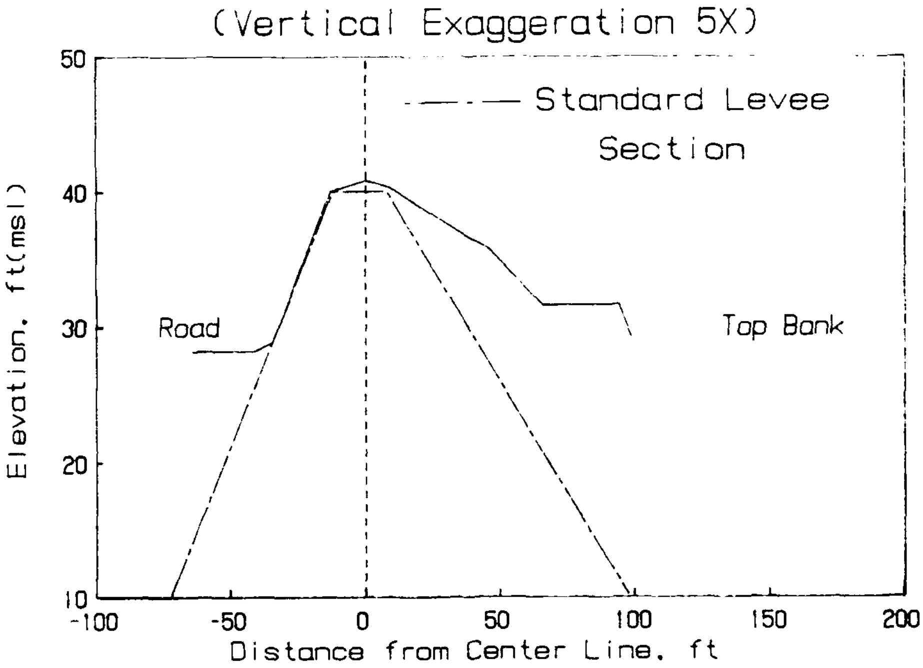


Figure 17. Levee cross-section profile, control site (site 2)

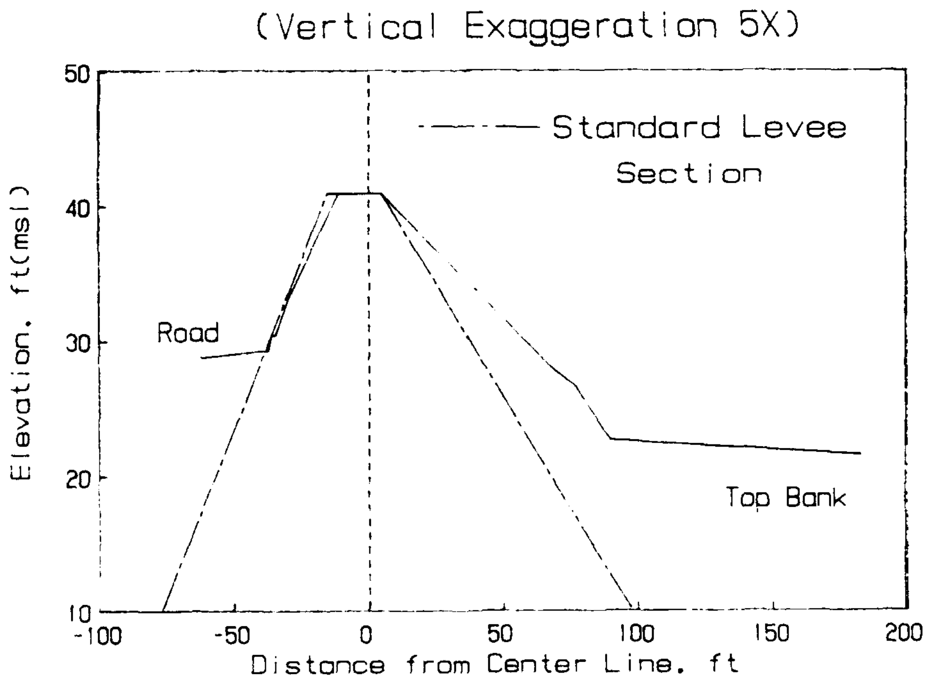


Figure 18. Levee cross-section profile, live oak site (site 4)

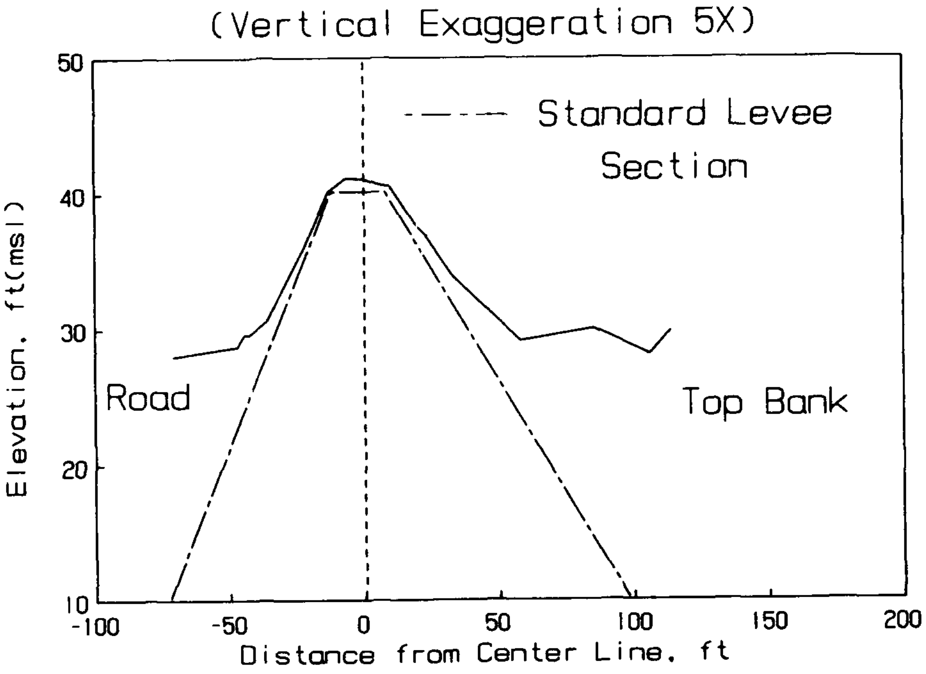


Figure 19. Levee cross-section profile, willow site (site 5)

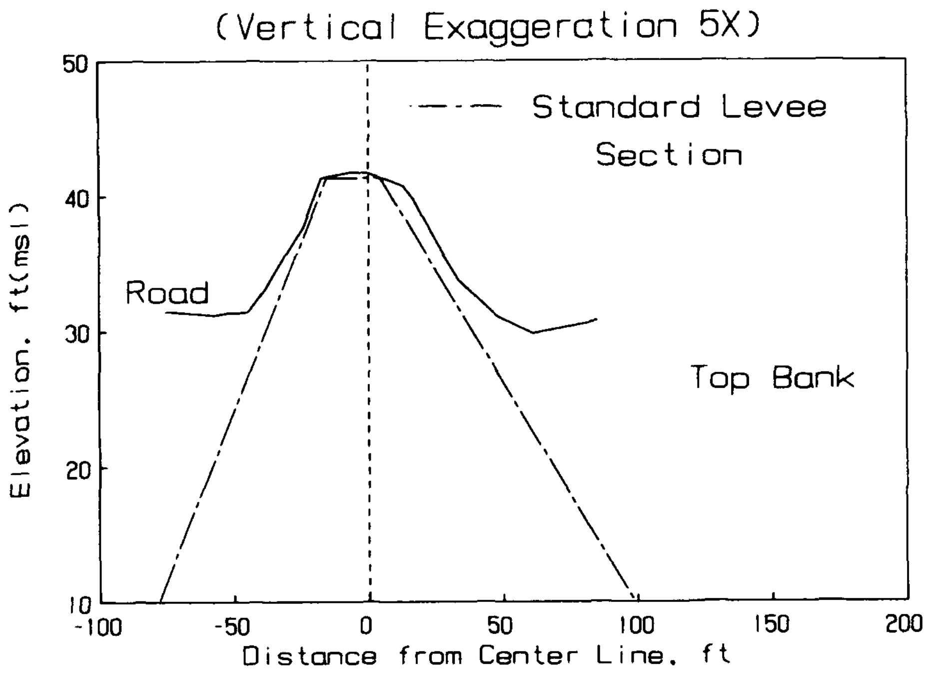


Figure 20. Levee cross-section profile, elderberry site (site 7)

Figure 21. Fissure in large clay clod or inclusion that has been permeated by a tree root

Figure 22. Example of vertical zonation or stratification on riverward levee slope caused by deposition of sediments during overbank flows

The Unified Soil Classification system design tion for the levee soil is SP. The gradation curves shown in Figure 23 for samples from site 3 are typical.

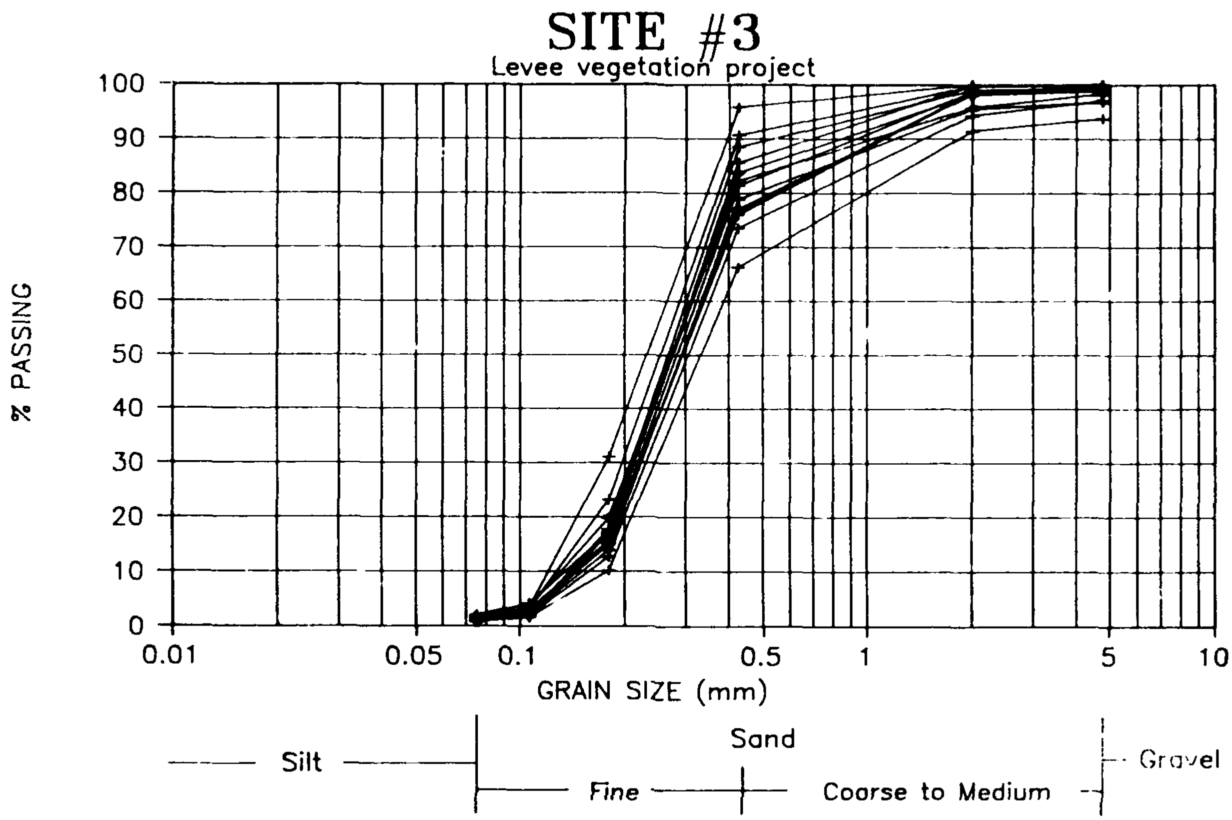


Figure 23. Grain size distribution curves for levee samples from site 3 (samples obtained from different boring locations and depths at site)

86. Field density. The sandy levee soil is generally in a fairly loose condition. The average dry density for all samples was)0 pcf. The site averages ranged from 85 to 92 pcf. Higher sample densities correlated or corresponded to sites that contained larger amounts of fines. No obvious or discernible relationship was observed between density and depth.

87. Permeability. The permeability of selected reconstituted samples of dry, sandy levee soil was determined usi a gas permeameter. The permeability ranged from 0.03 to 0.07 cm/sec depe ding upon the void ratio. This permeability range is typical for a medium sand, and is consistent with the results of the gradation analyses. The sandy soil obeyed the Kozeny-Karman equation which predicts a linear relation between permeability (K) and (e3/1+e); where e is the void ratio. This functional relationship is shown plotted in Figure 24 for one of the samples that was tested.

88. Shear strength parameters. Effective shear strength parameters, namely, friction (Ø') and cohesion (c'), were determined using an Iowa bore

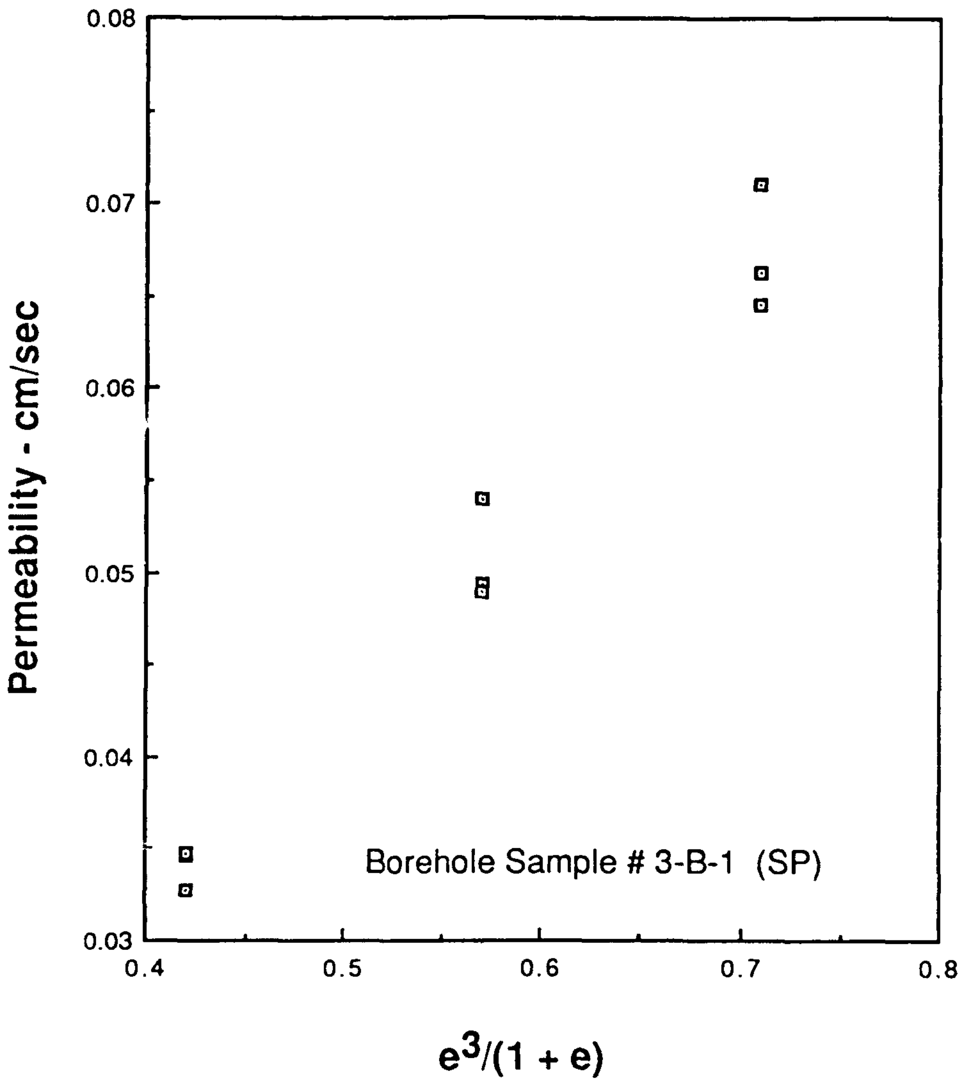


Figure 24. Typical functional relationship between permeability and void ratio for sandy levee samples

hole, direct shear device. Failure envelopes were obtained rapidly as a function of depth and checked on site. Typical failure envelopes for two depths in a test boring at Site 3 are shown in Figure 25.

89. The frequency distribution for both the cohesion and friction values from all borings are shown in Figures 26 and 27, respectively. The averages of all borings on the levee are:

Average friction angle = 31.6 deg
Average cohesion = 1.2 psi

The standard deviations were 3.7 deg and 0.62 psi for friction and cohesion, respectively. These results are reasonable for a medium, fine sand. The

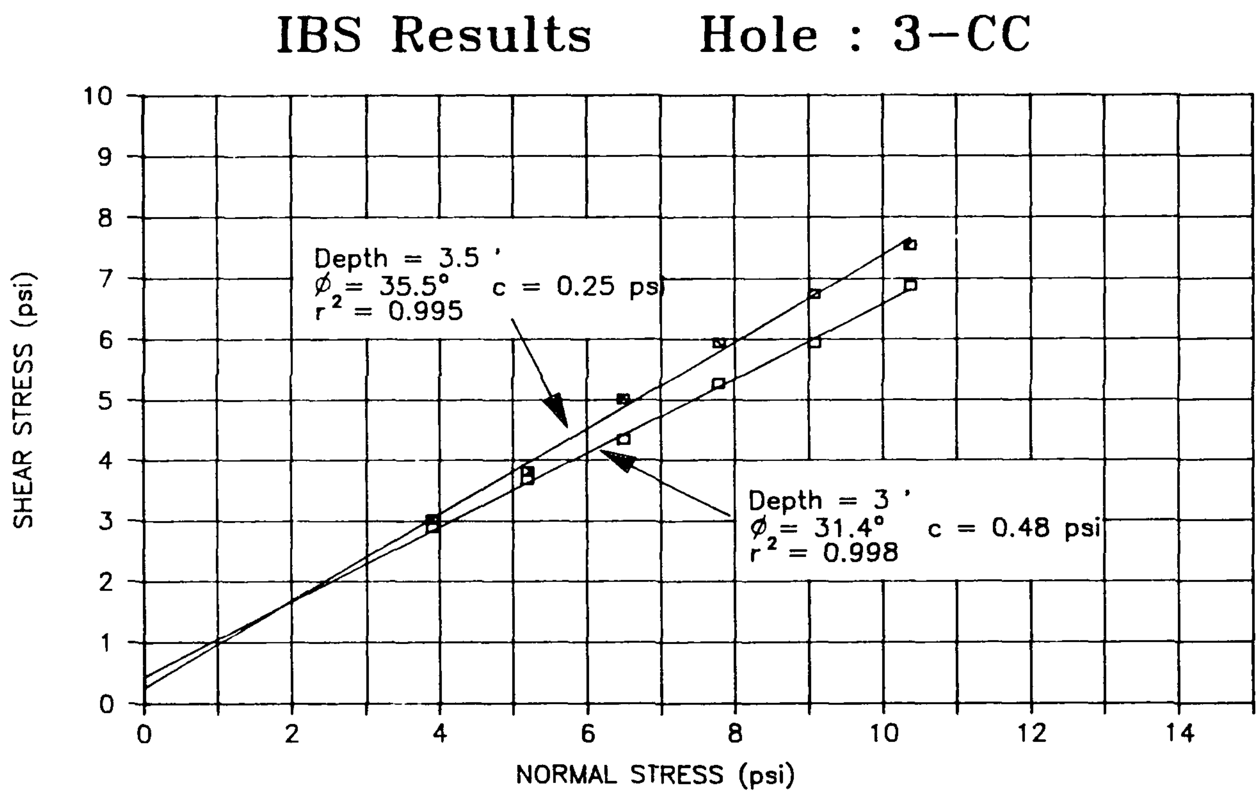


Figure 25. Example of failure envelopes obtained from Iowa borehole shear test borings at site 3

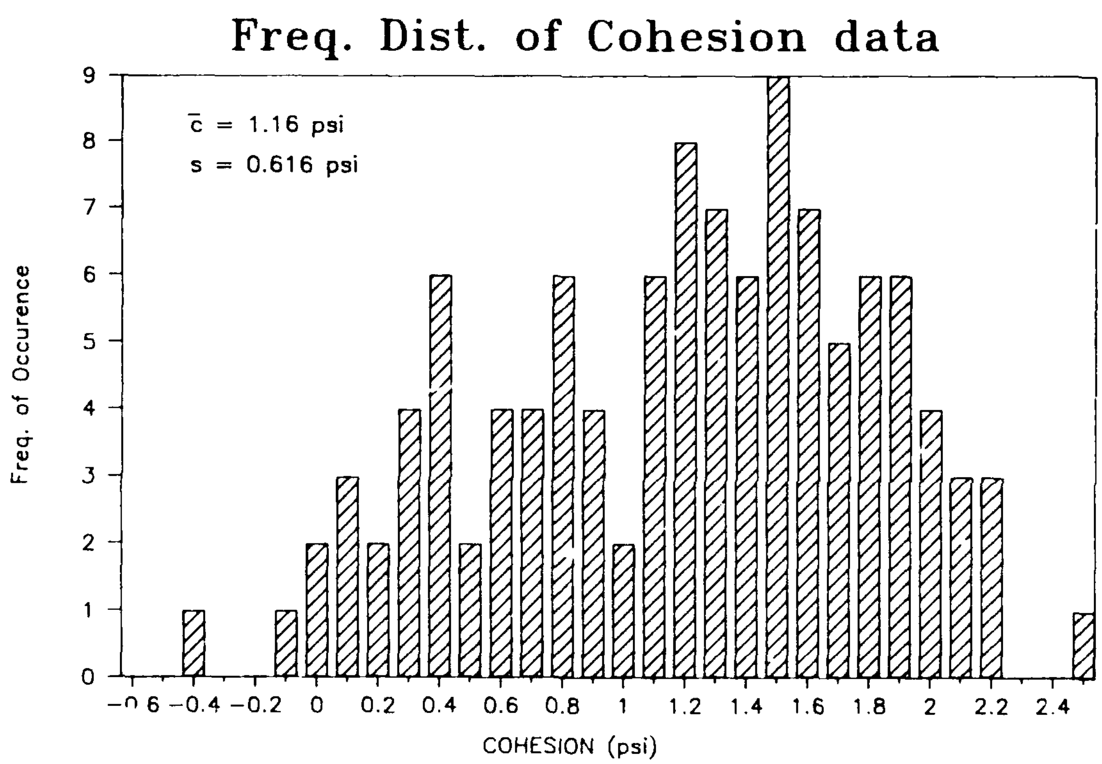


Figure 26. Frequency distribution of cohesion values obtained from all borehole shear test borings

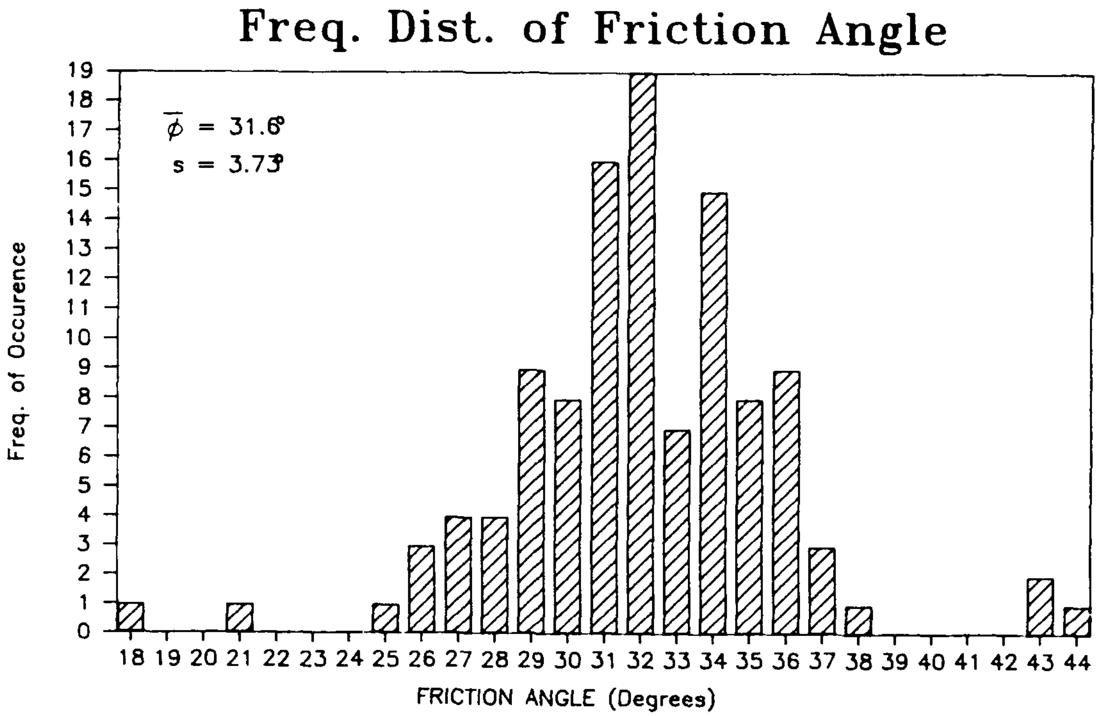


Figure 27. Frequency distribution of friction values obtained from all borehole shear test borings

general higher values of friction were observed where *cohesion was* low and vice versa. A plot of friction versus cohesion for all results (test borings) is shown in Figure 28. A linear regression analysis (R = 0.645) of this data yielded the following relationship.

$$\phi = 36.0 - 3.82c \qquad (1)$$

where: ϕ = friction angle (degrees and c = cohesion (psi)

90. High cohesion values were associated with soil samples having a higher content of fines. As noted previously, these same samples also tended to have higher densities. Not surprisingly, therefore, a correlation was also observed between average site cohesion and average site density. Cohesion increases with increasing density as shown in Figure 29. The number above each point in the plot corresponds to the site number. The sites with large amounts of fines (sites 5, 7A, and 7B) exhibit the highest cohesion and soil density, whereas sites with lesser amounts of fines (sites 2, 3, and 4) have lower cohesions and densities.

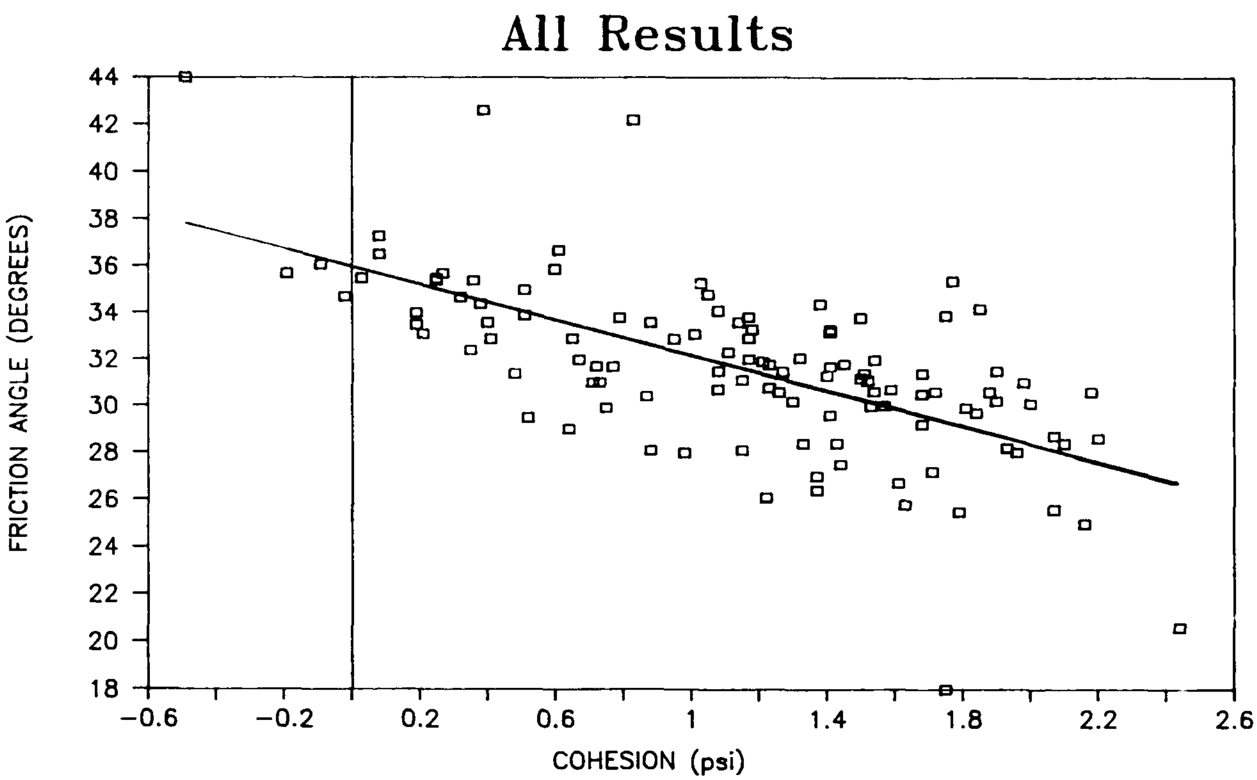


Figure 28. Friction vs. cohesion results for all test borings showing best-fit linear regression curve

91. Some evidence of root reinforcement was observed in the failure envelopes of a few test borings using the bore hole shear device. A photograph of a test boring site illustrating the extent of root permeation around the former bore hole is shown in Figure 30. The Iowa bore hole shear device is not ideally suited or designed to detect and measure root reinforcement influences on shear strength because the roots no longer penetrate fully across the failure surface after boring and reaming a hole to accommodate the shear head. Nevertheless, root/fiber reinforcement effects still manifested themselves in the form of bilinear or curved-linear failure envelopes in some instances, as illustrated in Figure 31. A distinct bilinear failure envelope was observed at a depth of 1 ft at this location (site 4).

92. Bilinear or curved-linear failure envelopes are typical of fiber reinforced sands as demonstrated by the work of Gray and Al-Refeai (1986); Gray and Maher (1989). Their work indicated that failure envelopes become strongly bilinear, as opposed to curved-linear, as the gradation and angularity of soil particles increase. The vertical displacement of the failure envelope above the reference or unreinforced envelope can be interpreted as a

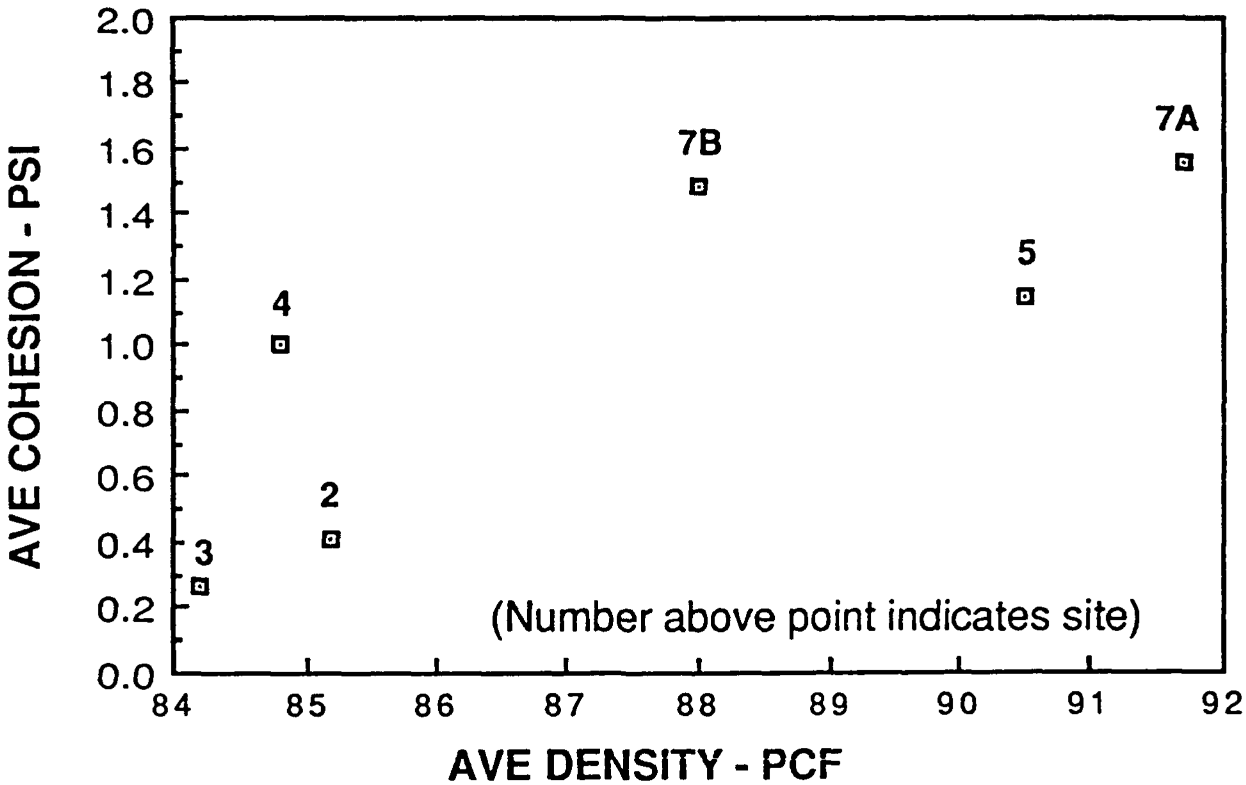


Figure 29. Average site cohesion versus average site soil density for in situ levee soils

Figure 30. Root permeation of sandy soil around former borehole location, site 4

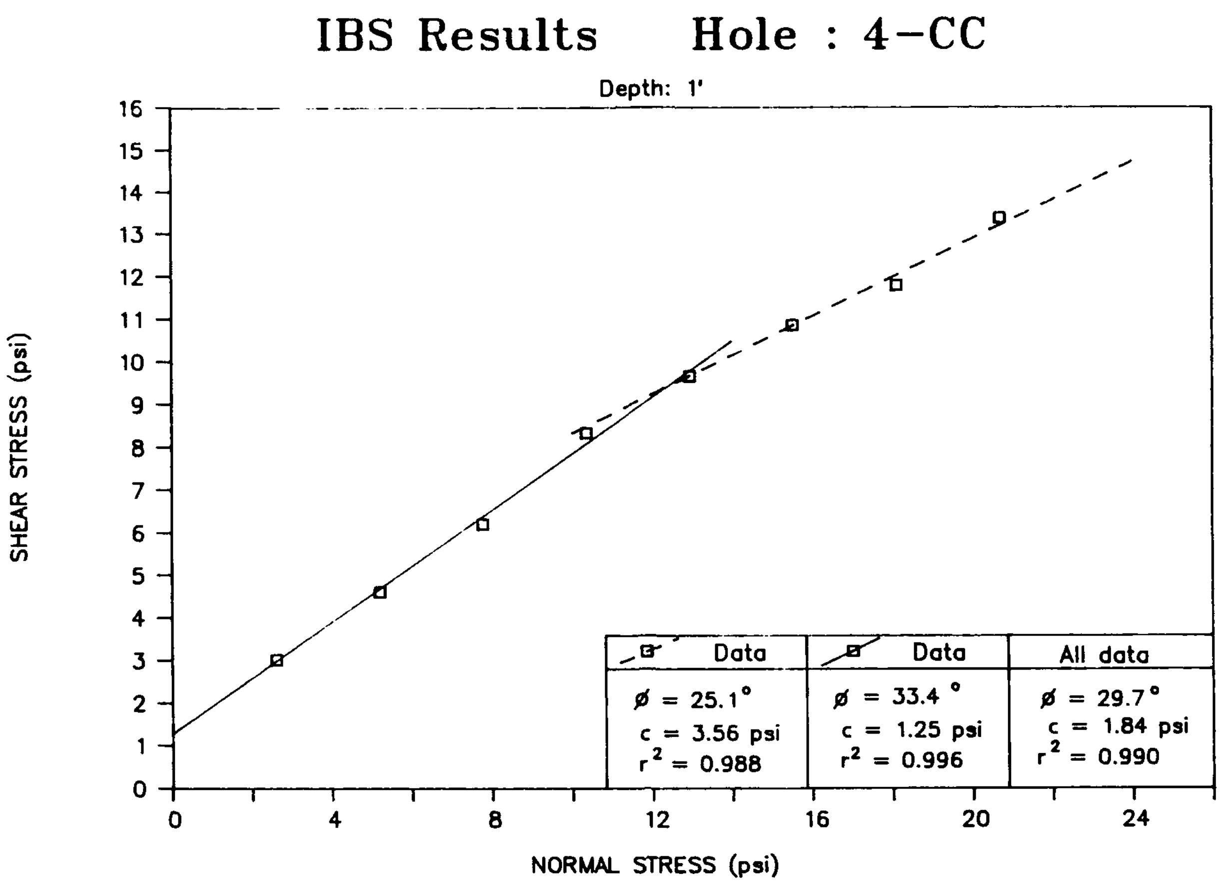


Figure 31. Bilinear failure envelope obtained in borehole shear test at site 4

measure of the additional shear strength or "fiber cohesion" imparted by the presence of the roots.

Botanical Data

Aboveground (vegetation)

93. Transect surveys. A total of seventeen 10-ft-wide transects were randomly selected (as described previously) for determination of the vegetation species composition and percent cover. The transect surveys showed that valley oak (*Quercus lobata*) and cottonwood (*Populus fremontii*) were the dominant tree species on the levee test section. Valley oak appeared well adapted to all levee environments and was the only arboreal species found growing on both landward and riverward slopes of the levee in addition to the levee crest area. All the other tree or shrub species, with the exception of California rose (*Rosa californica*) and licorice (*Glycyrrhiza* sp.), were found on the

riverward slopes only. Among the shrubs, licorice appeared to be particularly well adapted to all levee environments and vegetation management practices. This plant has an extensive root system and thrives on burning. A few weeks after firing the levee, licorice sprouted vigorously from its intact underground root system.

94. Vegetation cover for all transects by position on the levee, i.e., landward slope, crest area, and riverward slope, is summarized in Table 2. This summary table shows that ground cover (grasses and forbs) account for most of the plant cover, with shrubs occupying an insignificant proportion of the transect areas. Tree cover was 11 percent on the riverward slope, but less than 1 percent elsewhere.

Table 2

Summary of Vegetation Cover for All Transects by Location on the Levee Section

Levee Section Location	% Tree Cover	% Shrub Cover	% Ground Cover
Landward slope	0.44	0.08	48.1
Crest area	0.15	0.00	36.7
Riverward slope	11.00	0.10	40.4

95. Trench vegetation surveys. In addition to randomly selected transects, the species composition and cover were also determined at each of the trench sites as described previously. The location of different plants and the trace of their crowns, in the case of shrub or tree species, were superimposed on layout maps of each trench site. The absolute and relative cover for each major species were computed in this fashion. These results are summarized in Table 3. Percent cover pertains only to herbaceous plants, shrubs, and shrubby tree species (e.g., willow and black locust). The valley oak canopy was not included in these estimates.

"Belowground" vegetation

96. The profile-wall method (Bohm 1979) was adapted to determine the distribution and concentration of plant roots below ground. Sites with valley oak, black locust, willow, and elderberry were selected for root mapping in

Table 3

Species Composition and Plant Cover at Trench Sites

Species	Common Name	Absolute Cover (percent)					
		Control	Dead Oak	Live Oak	Willow	Elderberry	Black Locust
Grasses (various)	--	16.8	Burned	--	Burned	Burned	ND
Sedges (various)	--	6.7	--	<0.1	Burned	--	--
Rosa californica	California rose	31.6	--	5.9	--	3.7	2.1
Heterotheca grandiflora	Telegraph weed	1.5	--	--	--	--	--
Lotus purshianus	Lotus	0.2	--	--	--	--	--
Glycyrrhiza lepidota	Licorice	--	--	13.3	--	--	--
Sisymbrium officinale	Mustard	--	--	~4.7	--	--	0.4
Convolulus spp.	Bindweed	--	--	<0.1	--	--	--
Salix hindsiana	Willow	--	--	--	~10	--	--
Sambucus mexicana	Elderberry	--	--	--	--	72.0	--
Ribes spp.	Blackberry	--	--	--	--	1.7	--
Robinia pseudoacacia	Black locust	--	--	--	--	--	72.4

the field. At each site, mapping trenches were laid out running both parallel and perpendicular to the crest of the levee. In general the trenches were located tangentially at the crown edge or drip line of the tree species of interest. At the elderberry site the perpendicular trench was excavated through the approximate center of the clump or grove of elderberry bushes whereas the parallel trench was excavated tangentially to the crown edge.

97. Total area ratio profiles. The belowground mapping results are presented in several ways. Histograms or frequency distributions of all mapped features (roots, voids, pedotubules, and mineral inclusions) were prepared from the acetate overlay used in the field mapping program. The occurrence of these features is reported as an "area ratio," i.e., the percent of the trench face or cross-sectional area occupied by a particular feature. Typical histograms for the perpendicular and parallel trenches, respectively, showing the area ratios for different features as a function of depth at the elderberry site (site 7) are shown in Figures 32 and 33. Total area ratio histograms for the other sites are collected in Appendix A. An area ratio histogram for all features and depths as a function of position along the trench in the perpendicular trench arm at the elderberry site is shown in Figure 34. The bulge or peak in the histogram at mid-distance simply reflects the proximity of the plant stems at this position and the greater concentration of roots close to the stems.

98. Root area ratio (RAR) profiles. The fraction of the trench face or total cross-sectional area occupied by roots is referred to herein as "root area ratio (RAR)." This ratio is normally reported in percent. The RAR results can be presented in a variety of graphical and tabular formats which emphasize different aspects of the information. The RARs as a function of depth for all sites are summarized in Table 4. The RARs typically did not exceed more than 2 percent of the total cross-sectional area at any depth. The largest ratio was recorded at the control site at shallow depth due to the presence of abundant roots of herbaceous cover and California rose plants. The next highest root area ratio (1.1 percent) was measured at the elderberry site at a depth interval of 8-12 in. in the perpendicular trench. This trench passed close to the centers of the clump of elderberry bushes.

99. The RARs tended to decrease with depth in nearly every case. This trend is shown in Figures 35 through 37. Average RAR versus depth is shown in Figure 35 for the control, oak, and elderberry/willow/black locust sites.

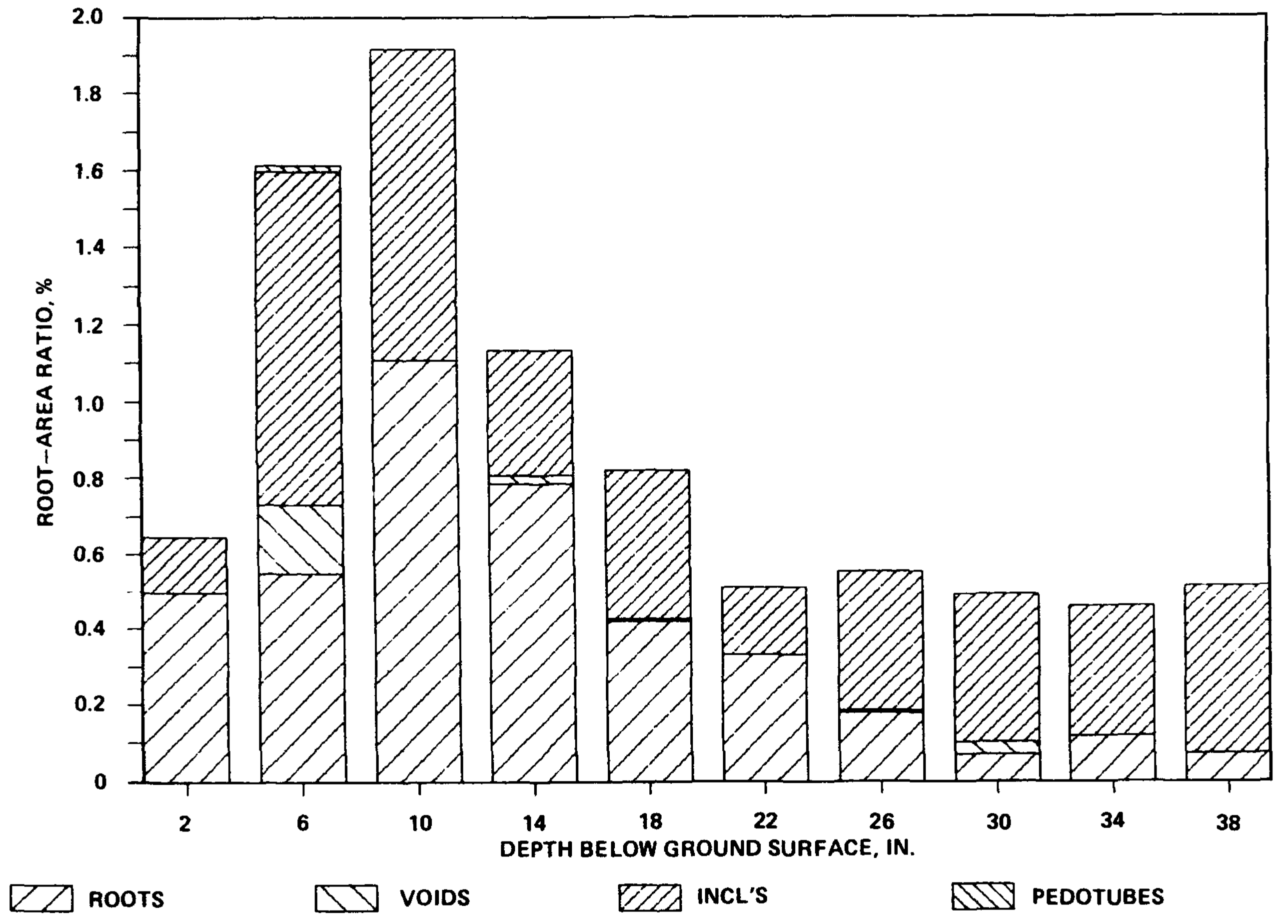


Figure 32. Total area ratio vs. depth, perpendicular trench, elderberry site (site 7)

Figures 36 and 37 show RAR-depth profiles for all sites (species) plotted on arithmetic and logarithmic scales, respectively. Average RARs decreased to less than 0.1 percent in all cases at depths greater than 40 in. These root distributions and concentrations are consistent with trends and values reported in the horticultural literature. A plot of RAR versus depth for the elderberry site at the parallel and perpendicular mapping trenches is shown in Figure 38. Root concentrations decreased approximately exponentially with depth at the perpendicular trench which passed close to the centers of the stems, whereas root concentrations tended to decrease linearly with depth in the parallel trench which was located at the drip line of the bushes. These root distributions were used later to estimate likely rooting contributions to shear strength.

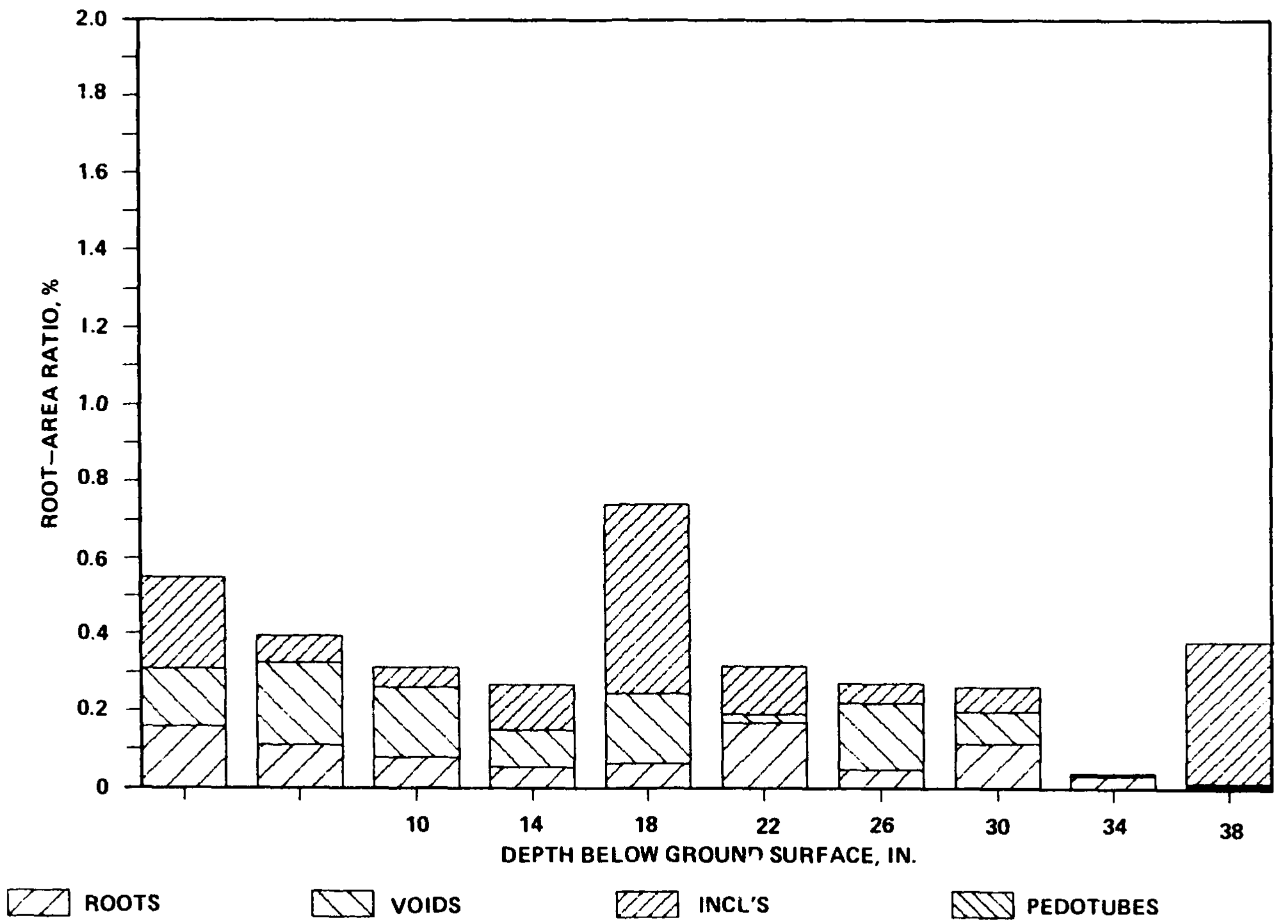


Figure 33. Total area ratio vs. depth, parallel trench, elderberry site (site 7)

100. The RAR is plotted versus species for different depth intervals in Figures 39 through 41. Flat, horizontal curves would indicate that no one species produces more roots than another. No consistent pattern or trend emerges from these plots...in the sense that one species can be said to have much higher root area ratios over its entire rooted depth compared to other species. The elderberry site tended to exhibit slightly higher ratios over its entire rooted depth compared to the other species but this result was biased somewhat by the location of the perpendicular trench close to the centers of the elderberry bush stems. Plots of RAR's versus species for different depth intervals for the other sites are collected in Appendix B.

101. Root size frequency distributions. The RAR is a useful, but highly aggregated parameter. Also of interest is the distribution of different size classes of roots with depth by species. This information was

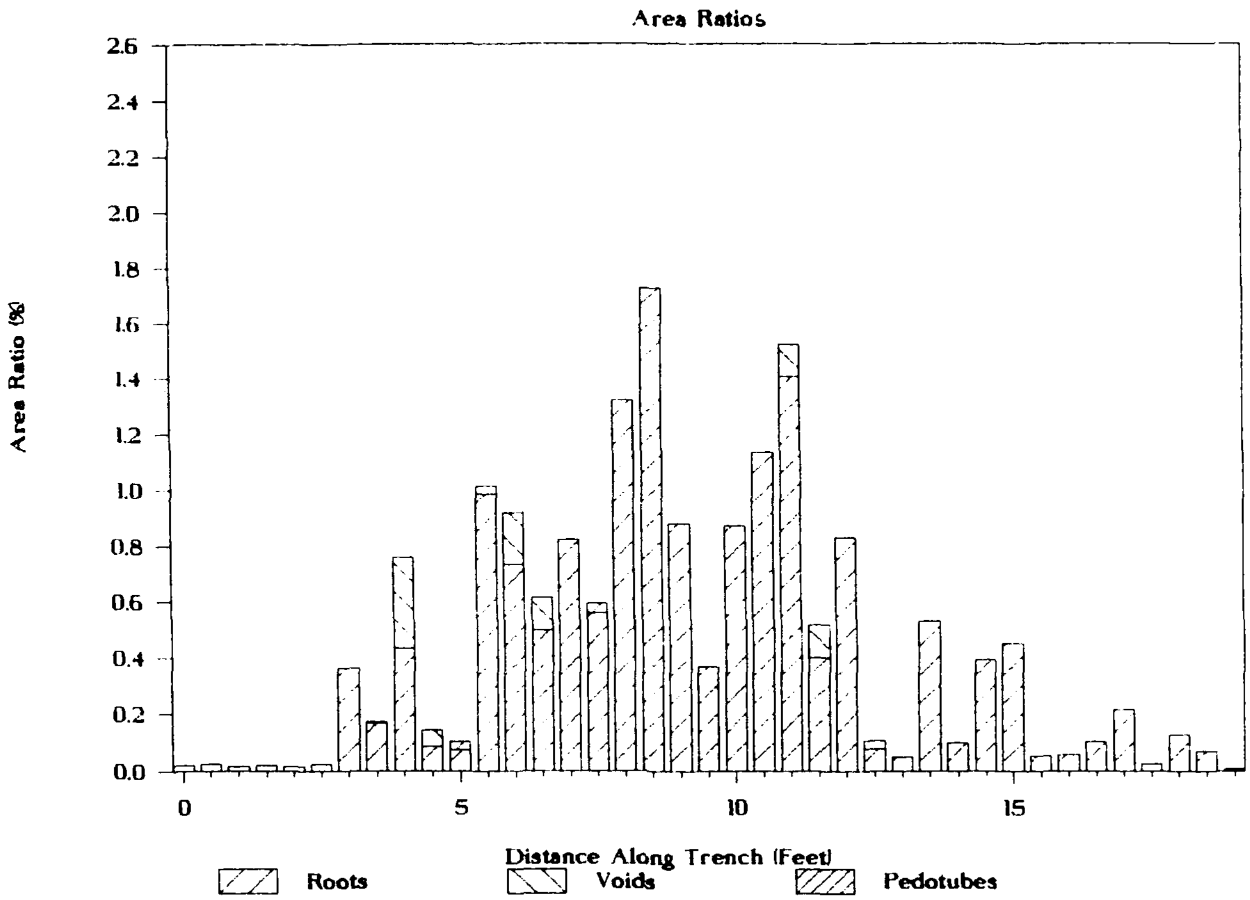


Figure 34. Total area ratio versus distance along trench, all depths, perpendicular trench, elderberry site

recorded directly on the acetate overlays during the field mapping program. Root size distribution plots are shown in a 3-D format in Figures 42 and 43 for parallel trenches at the live oak and elderberry sites, respectively. These two sites represent two extremes of woody vegetation, namely, large mature trees versus low shrubby bushes. Both trenches also were located at the drip line or crown edge. The root area ratio profiles for these two sites are similar in trend; however, the oak site has almost twice the total root area (summed over all depth intervals) as the elderberry site. This difference is due to the presence in general of larger roots at the oak site as can be seen by comparing Figures 42 and 43 and noting the greater number of roots in the larger size classes (classes 1-3) at the live oak site. Root size distribution plots for the other sites are collected in Appendix C.

102. Root architecture (structure). In order to gain some insights into root architecture or structure, a dead oak stump was completely excavated

Table 4

Root Area Ratios (Percent) Versus Depth at Trench Sites

	Control		Dead Oak		Live Oak		Willow		Elderberry		Black Locust	
Depth	Par.	Perp.	Par.	Perp.	Par.	Perp.	Par.	Perp.	Par.	Perp.	Par.	Perp.
0-4	2.02	0.10	0.04	0.001	0.32	0.01	0.03	0.20	0.16	0.50	0.03	0.85
4-8	0.02	0.62	0.02	0.01	0.23	0.04	0.10	0.18	0.11	0.55	0.12	0.07
8-12	0.01	0.18	0.40	0.01	0.28	0.01	0.36	0.26	0.08	1.11	0.07	0.62
12-16	0.10	0.12	0.11	0.003	0.25	0.01	0.01	0.20	0.05	0.78	0.02	1.02
16-20	0.19	0.01	0.04	0.01	0.15	0.02	0.01	0.10	0.06	0.42	0.02	0.87
20-24	ND	0.06	0.03	0.01	0.06	0.12	0.01	0.05	0.17	0.33	0.002	0.01
24-28	ND	0.39	1.06	0.001	0.09	0.02	0.01	0.03	0.05	0.18	0.001	0.02
28-32	ND	0.06	0.004	0.03	0.09	0.04	0.01	0.004	0.11	0.07	0.001	0.13
32-36	ND	0.10	0.09	0.24	0.13	0.02	0.001	0.06	0.03	0.12	0.001	0.01
36-40	ND	0.15	0.001	0.16	0.08	0.13	0.004	0.34	0.01	0.07	0.001	0.001

Depth below levee surface, inches (4 in. = 0.102 m)
ND: No data

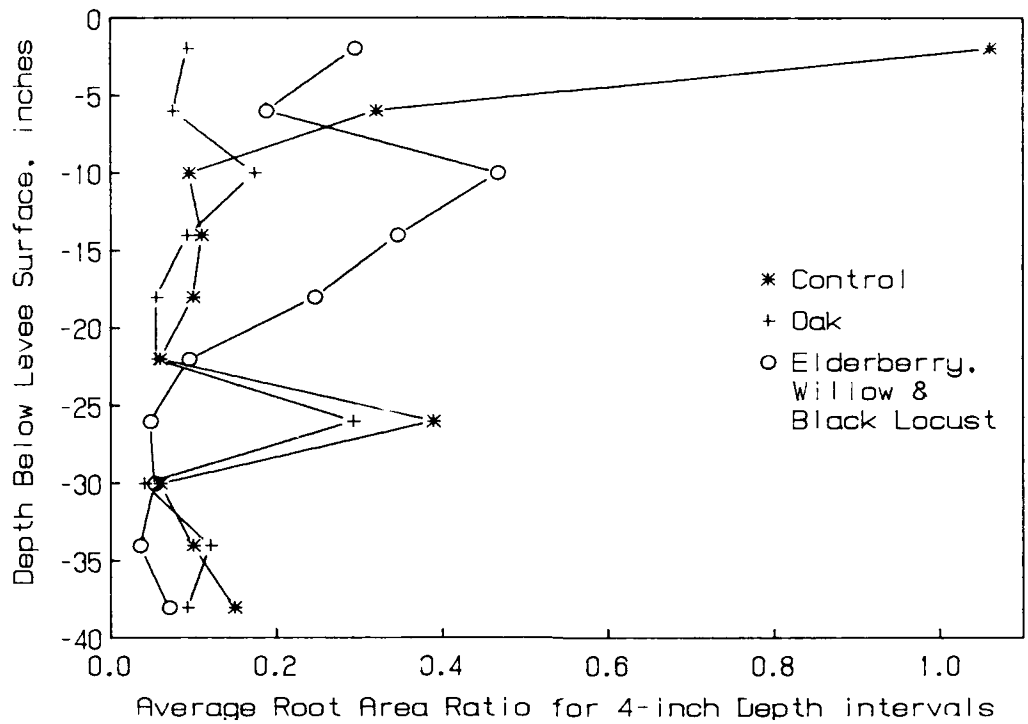


Figure 35. Average RAR profiles for control, oak and elderberry/ willow/black locust trench sites

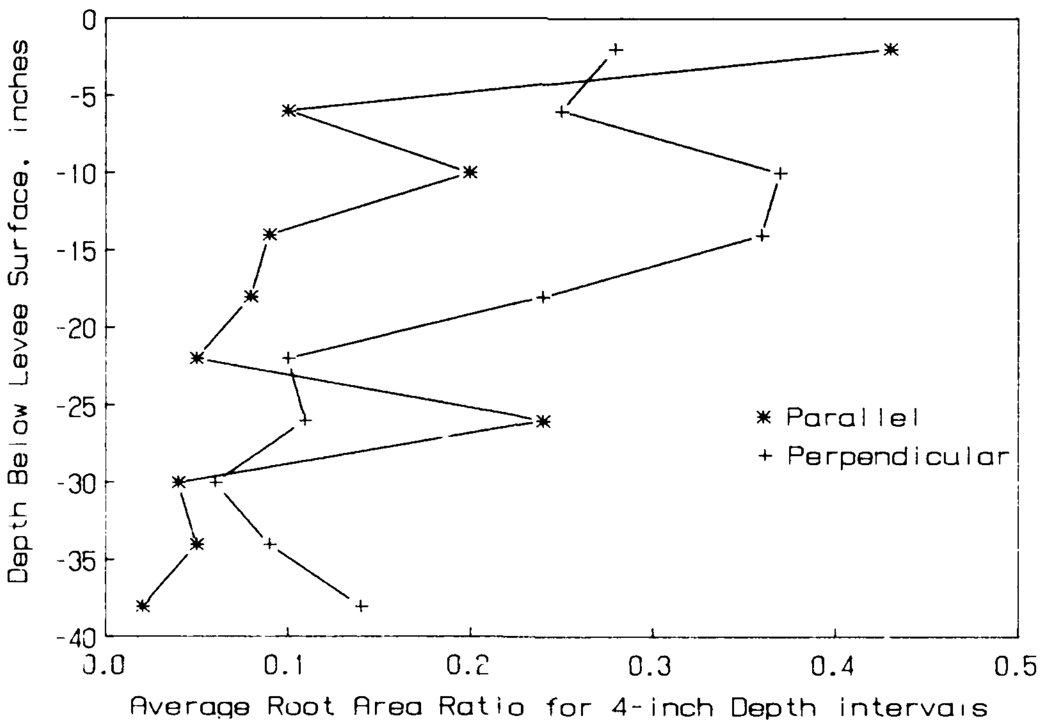


Figure 36. Average RAR profiles for parallel and perpendicular trenches, all sites, arithmetic scale

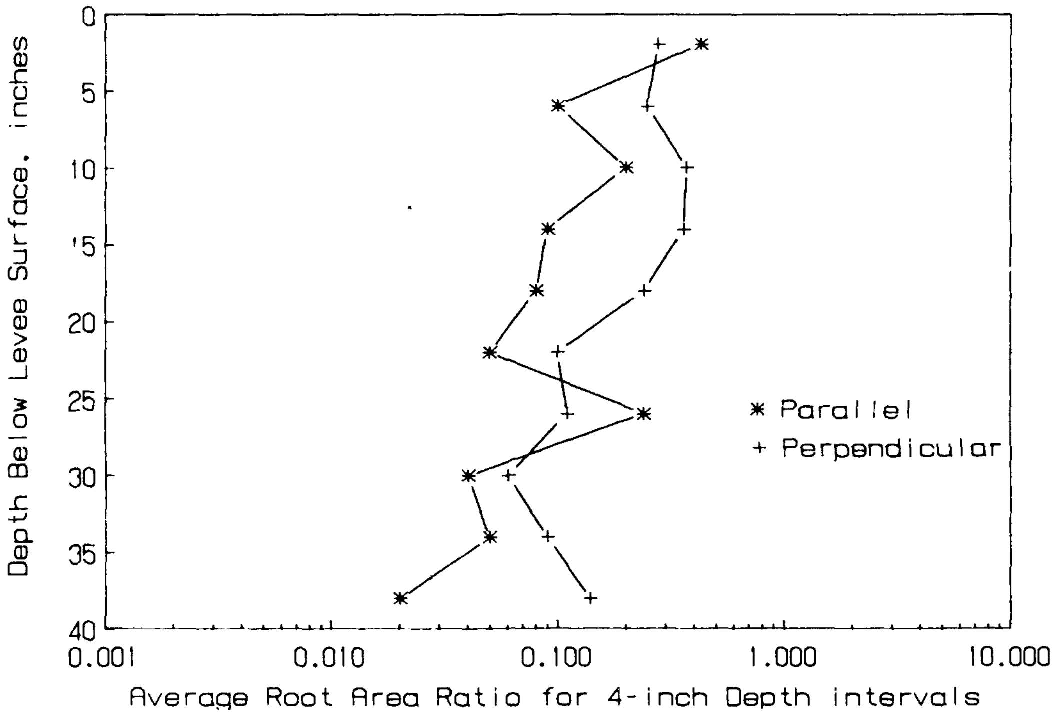


Figure 37. Average RAR profiles for parallel and perpendicular trenches, all sites, logarithmic scale

after trenching (site 2). The dead oak stump was located near the crest of the levee adjacent to the road on the riverward side. The stump was visible as a living tree in 1974 air photos and as a stump in 1982; therefore, it was felled sometime during the 8-year period between 1974 and 1982. Accordingly, the age of the stump when it was excavated in 1987 was somewhere between 5 and 13 years old. Based on a tree ring count, the age of the tree when it was cut was at least 37 years.

103. The root architecture of the oak was characterized by a massive, central tap root and a series of lateral roots radiating from the main tap root at a depth below the ground surface of approximately 0.6 to 1.2 m. A photograph of the excavated stump is shown in Figure 44. The most interesting and significant feature of the laterals was the angle at which they radiated away from the central tap root with respect to the ground surface. Most of these lateral roots angled down sharply rather than growing out in a quasi-horizontal attitude characteristic of lateral roots. This structure explains in part the paucity of roots exposed in the vertical mapping faces of the trenches around the oak trees at their drip lines. This structure is also consistent with the adaptability of the oaks to the levee environment and extreme droughtiness of the sandy soils that comprise the levee. The lateral

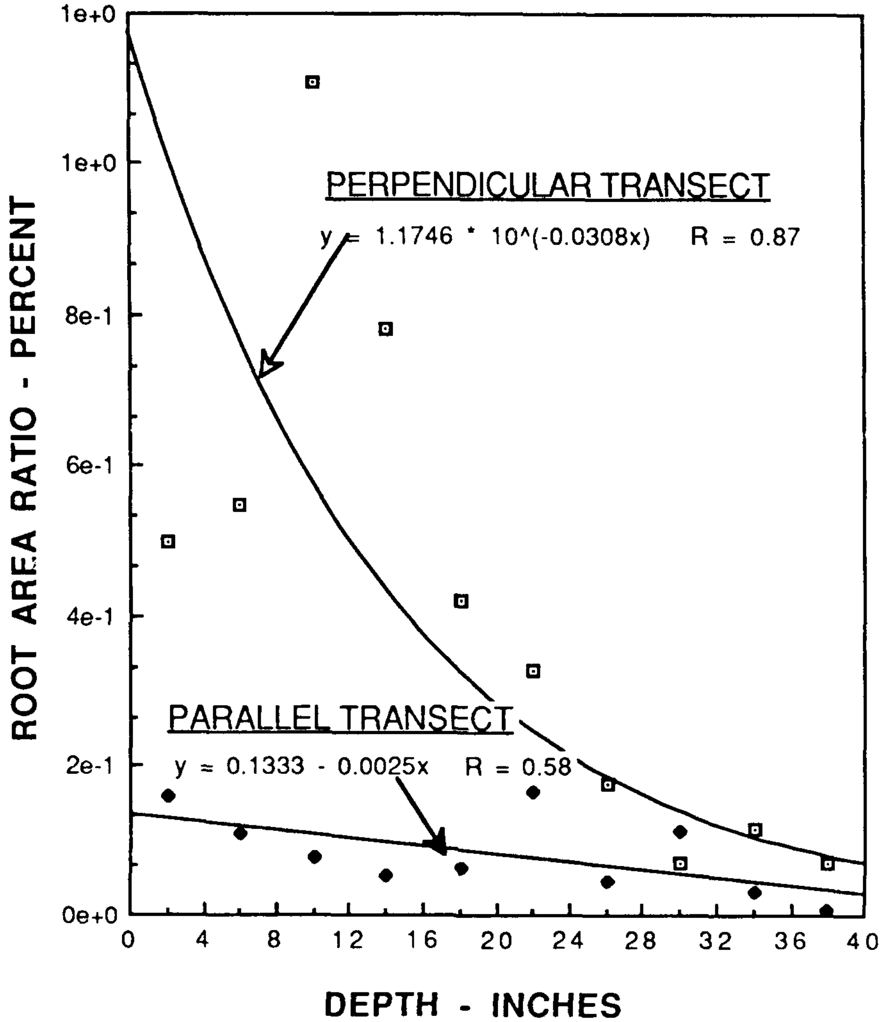


Figure 38. Functional relationship between RAR and depth in perpendicular and parallel transects, respectively, elderberry site (site 7)

roots are angling down sharply in order to reach the groundwater table at depth beneath the levee.

104. Vertical versus horizontal roots. Vertical or sinker roots are more likely to be effective in directly resisting downslope shearing forces on surfaces oriented parallel to the slope. The profile-wall method essentially maps horizontal or near horizontal roots exposed in a vertical face of a trench. The question that arises accordingly is, "Are RARs mapped on a vertical surface also representative of RARs in a horizontal plane which would be more representative of the vertical root system?" Reistenberg and Sovonick-Dunford (1983) conducted extensive root mapping of ash and map-

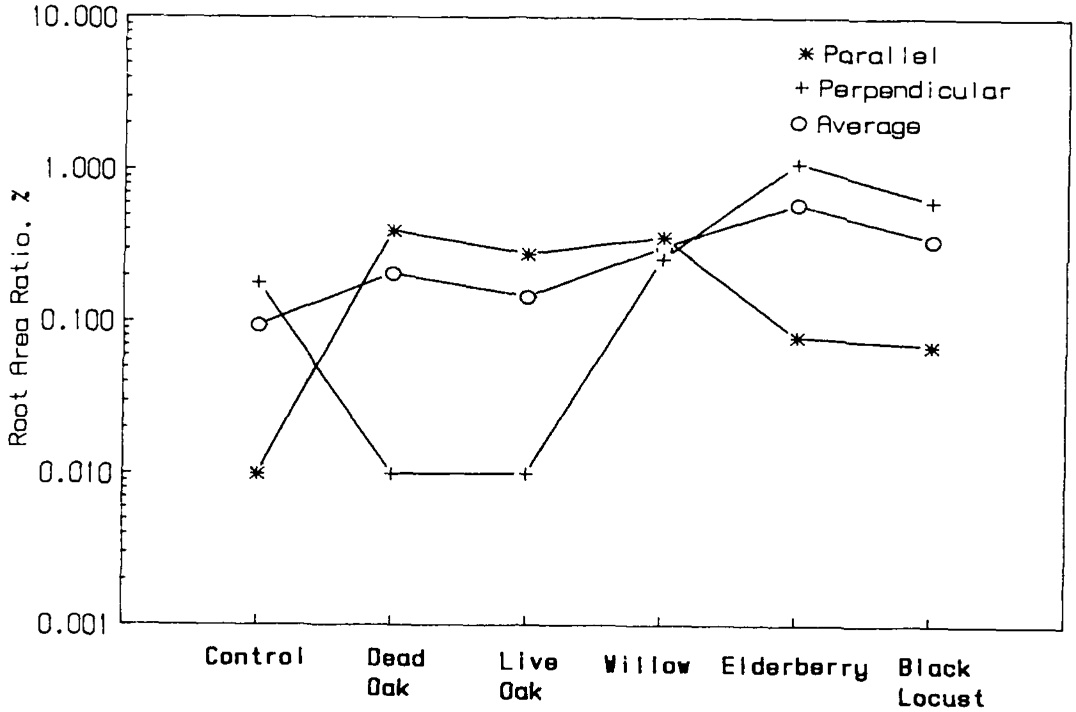


Figure 39. The RAR versus species for 8- to 12-in. depth interval

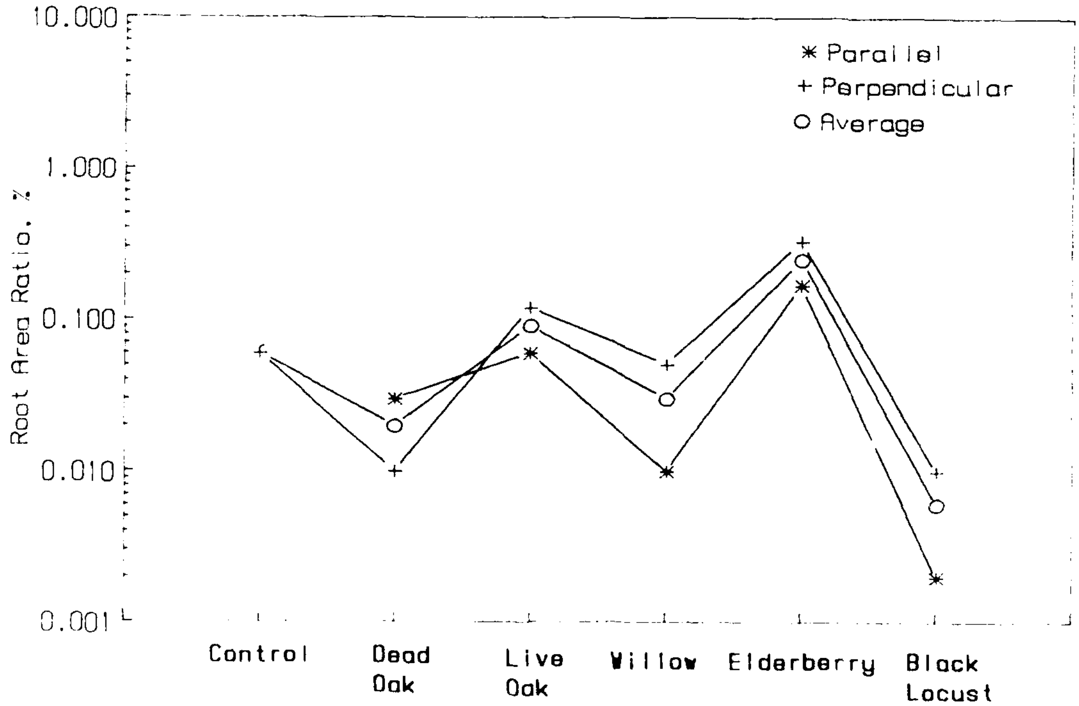


Figure 40. The RAR versus species for 20- to 24-in. depth interval

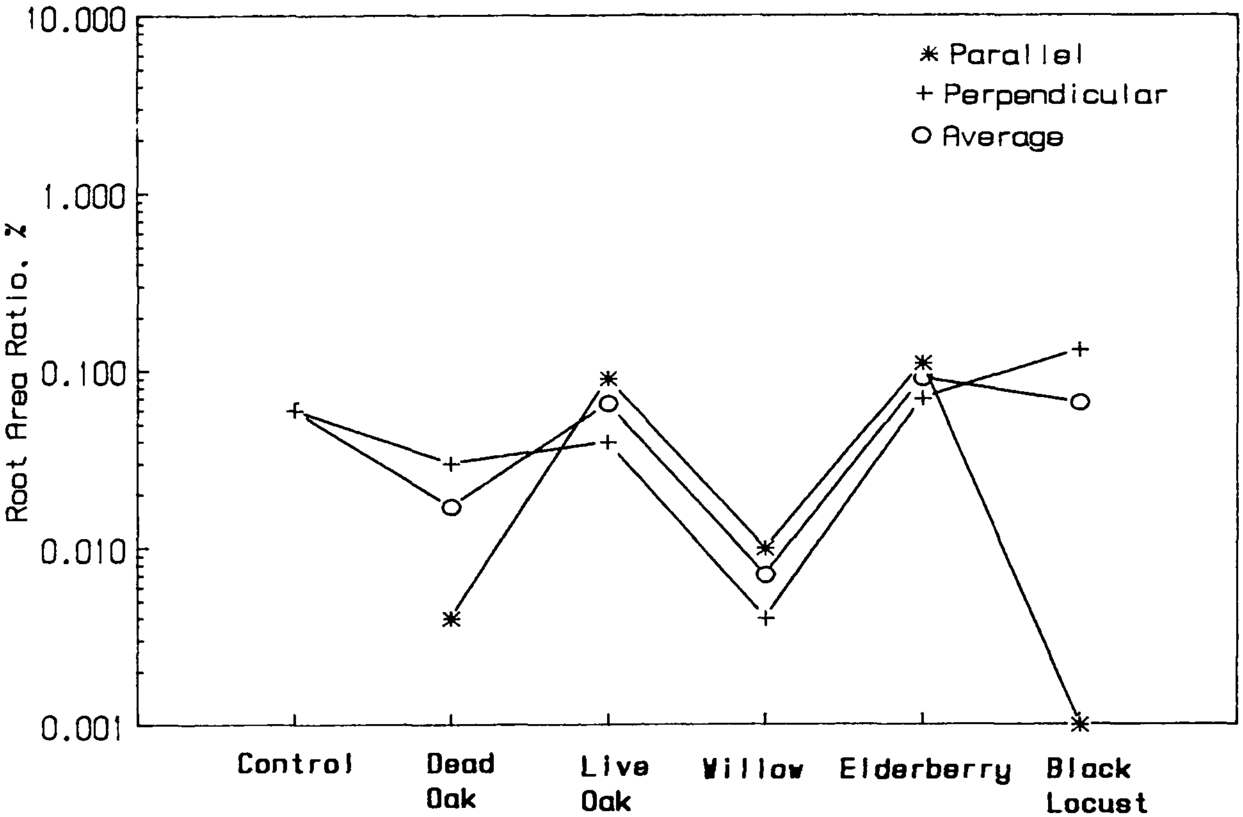


Figure 41. The RAR versus species for 28- to 32-in. depth interval

trees growing in a colluvial layer of soil on a steep, slide-prone slope. They hand-excavated the root systems and measured root areas in horizontal planes as a function of depth. Their root area ratio profiles were very similar to those obtained in the present study. This finding suggests that root distributions obtained by the profile-wall method should provide reasonable estimates of root area ratios (on horizontal surfaces) with depth as well. Further study is required on this point, however, in view of the root structure revealed during the excavation of the dead oak stump.

105. Void and pedotubule distribution. Voids and pedotubules that were exposed in the trench faces were also mapped along with roots. Unlike intact roots, open voids or conduits in a levee represent a clear and immediate danger from the point of view of a piping or internal erosion failure. Voids or holes created by burrowing rodents were easily identified in the trench faces by their size, shape, and form. An example of a ground squirrel burrow exposed in the trench face at site 4 is shown in Figure 45. These burrow holes occurred at all depths. A burrow hole located at the bottom of the

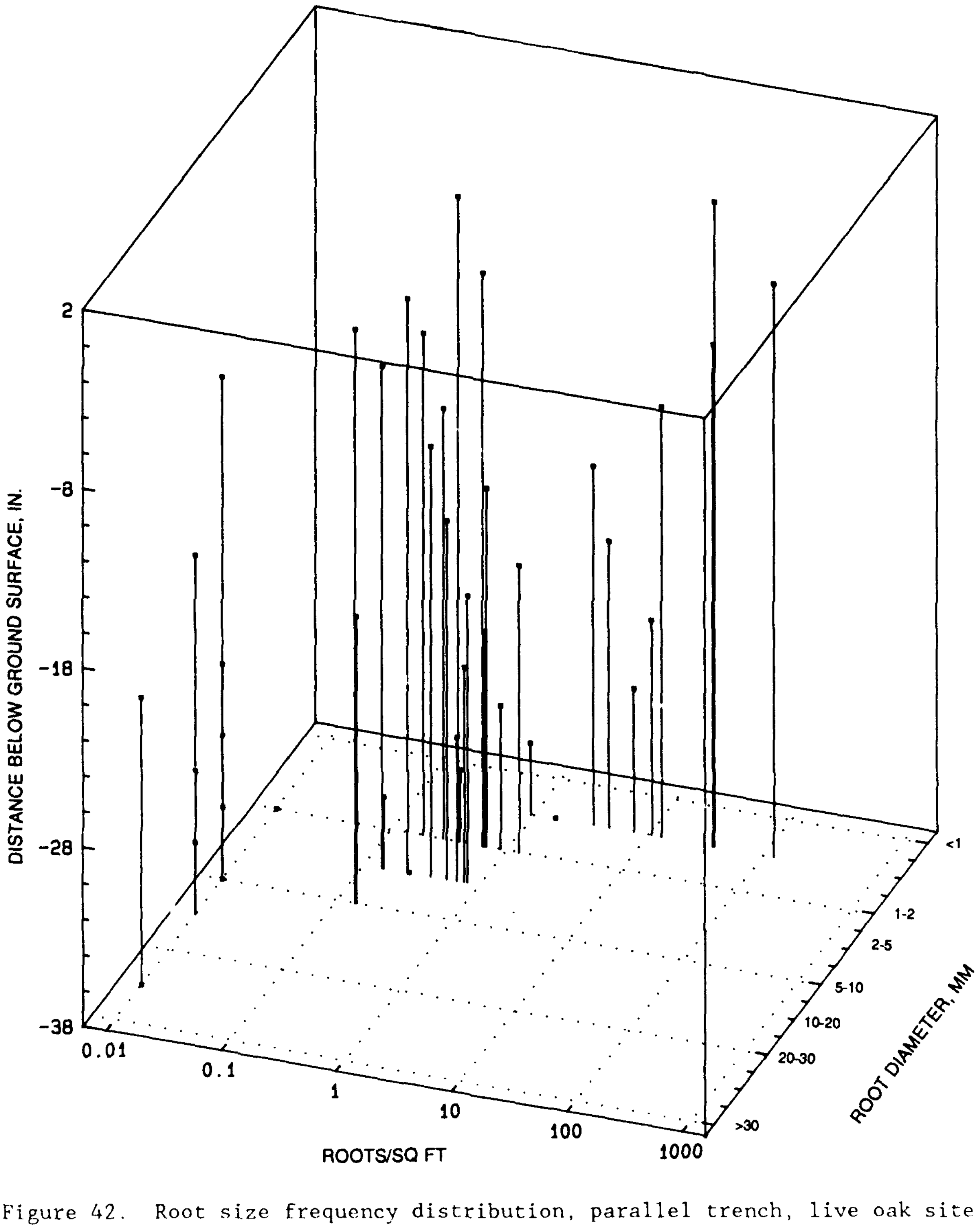


Figure 42. Root size frequency distribution, parallel trench, live oak site (site 4)

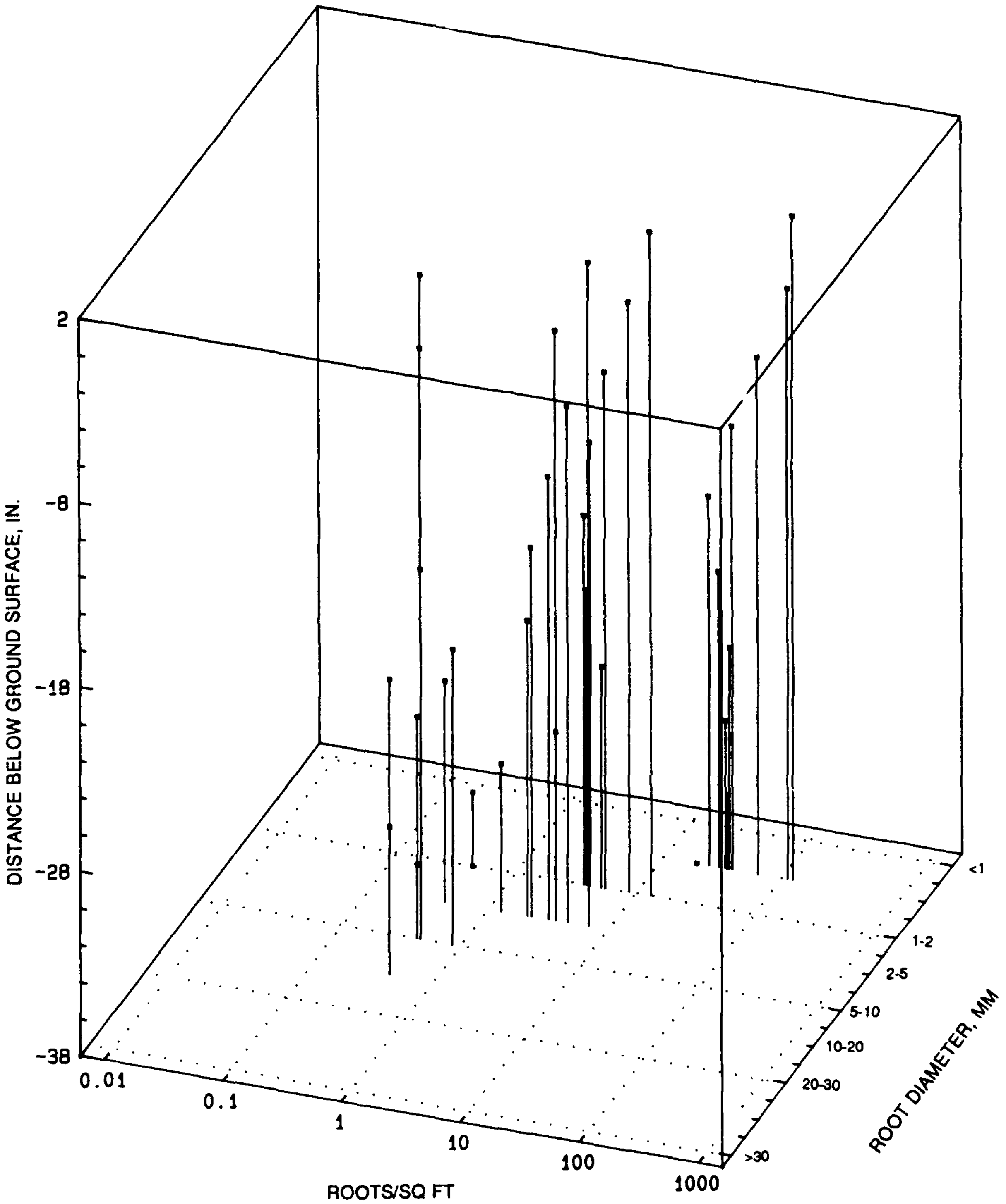


Figure 43. Root size frequency distribution, parallel trench, elderberry site (site 7)

Figure 44. Photograph showing root structure and architecture of dead oak stump excavated in sandy levee, site 2

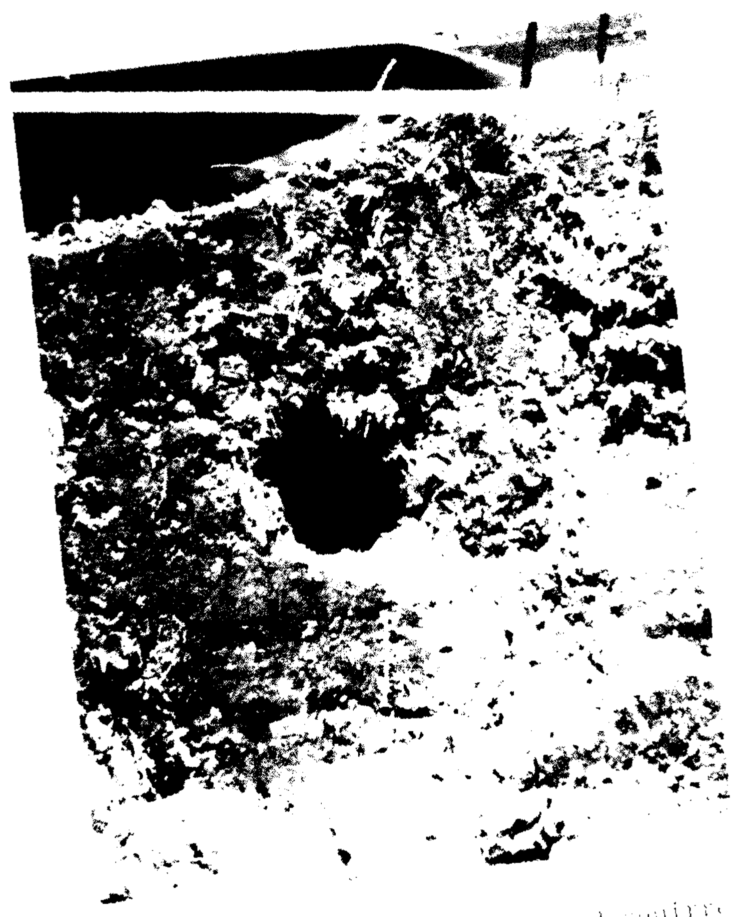


Figure 45. Photograph of ground squirrel burrows exposed in trench face at live oak site (site [illegible])

parallel trench face at the live oak site (site 4) is shown in Figure 46. Smaller diameter voids or holes caused by insects, e.g., ants, were also observed. These were very abundant in the parallel trench at the elderberry site (site 7).

106. No voids clearly attributable to decayed or rotted roots were observed. In a few cases voids were observed with residual root bark linings. However, these voids were all infilled with soil and hence, are more appropriately classified as pedotubules. An example of an infilled root hole is shown in Figure 47.

107. Void versus depth profiles were plotted for each site. The void density versus depth is shown plotted in Figure 48 for the elderberry and live oak sites. The average void count for all sites is also plotted on Figure 48.

Figure 46. Photograph of ground squirrel burrow exposed at bottom of trench parallel to levee crest at live oak site

Figure 47. Photograph of infilled root hole that has evolved into a pedotubule

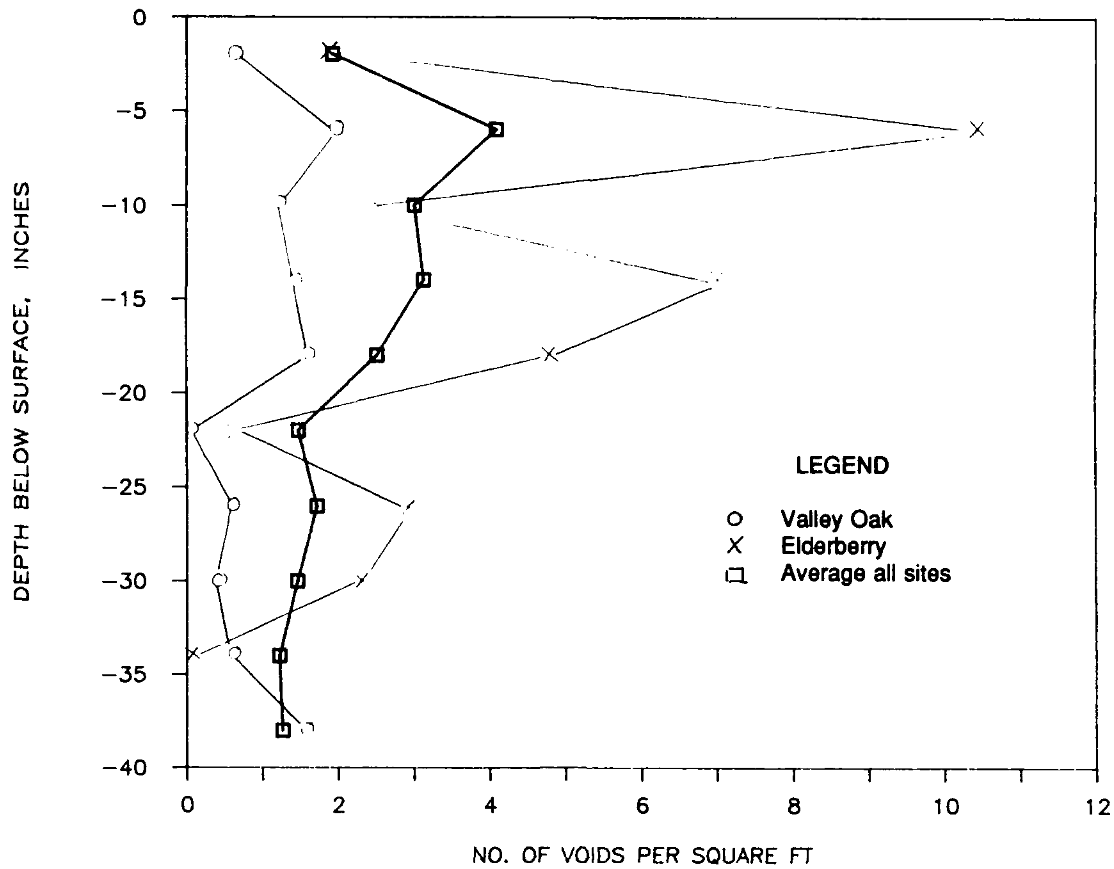


Figure 48. Void density versus depth for various trench sites

The number of voids per square foot reaches a maximum at a depth of 6 in. and then decreases with depth to some minimum value. The number of voids per square foot tends to exceed the average at the elderberry site, and drops below the average at the live oak site. This finding can be explained as follows: voids at the elderberry site are smaller and more numerous as a result of insect activity, whereas the voids at the live oak site tend to be larger and less numerous as a result of animal (ground squirrel) burrowing. An examination of the total area ratio profiles--which include void area ratios-reveals that the live oak site had a total or combined void area ratio of 4.7 percent versus 1.3 percent for the elderberry site. This finding also supports the position that voids are less numerous but much larger on average at the oak site compared to the elderberry site.

108. Good examples of pedotubules were observed in the perpendicular trench face at the live oak site. Some of these pedotubules had approximately circular or slightly elliptical cross sections with roughly the same diameters

as the squirrel burrows also observed in the same trench face. The pedotubules could be distinguished visually from the surrounding soil by differences in color and texture as shown in Figure 49. The soil from these pedotubules was analyzed further to determine if other soil properties might serve to distinguish them as well. One pedotubule (No. 1) was located approximately 9 m from the levee crest at an approximate depth of 2.2 ft, and the other (No. 2) at a depth of 0.5 ft approximately 13.5 m from the crest.

Figure 49. Example of pedotubule (No. 1) exposed in the perpendicular trench face at the live oak site (site 4)

109. The results of gradation analyses and field density tests performed on soil from the two pedotubules and the surrounding soil is summarized in Table 5. There is a pronounced difference in both gradation and density between the soil in the pedotubule and the surrounding soil at pedotubule 1. The lower density in the pedotubule suggests that this material was washed in and hydraulically deposited during a flood. The contrast in gradation and density for pedotubule 2 is marginal; only a visual or textural difference exists in this case. In any case, these findings indicate that voids do not persist long in these sandy levee soils; instead they evolve into pedotubules with time. Only rapidly formed holes of recent origin, namely, animal burrows or insect holes, are likely to be seen and mapped as voids at any given instant. Root holes form more slowly as roots gradually decay and are more likely to evolve directly into pedotubules and not persist long as voids.

Table 5

Gradation and Density Characteristics of Pedotubules

Pedotubule No.	Location	D30 mm	Unified Classification	Dry Density pcf
1	In pedotubule	.200	SP-SM or SC	71.2
	Around pedotubule	.069	SM or SC	80.1
2	In pedotubule	.07	SM or SC	81.8
	Around pedotubule	.10	SM or SC	78.7

PART V: GEOTECHNICAL AND HYDRAULIC ANALYSES

Seepage Analyses

110. Predictive approach. One of the goals of the study reported herein was to determine the likely influence of vegetation on the hydraulic flow regime in a levee. This goal essentially entails determining the distribution of hydraulic head and the location of the phreatic surface in a levee cross section, i.e., constructing a flow net.

111. The location and spacing of flow lines and equipotential lines in a flow net is particularly important with respect to the internal stability of a levee and its resistance to piping and seepage erosion. Closely spaced lines translate into high gradients and seepage velocities. If this condition occurs near the discharge face of the levee, piping and seepage erosion can occur.

112. Possible ways in which vegetation can influence the hydraulic regime of the levee include:

a. Modification of the hydraulic conductivity of the near-surface layer (top 3 ft) as a result of root permeation and disturbance.

b. Alteration of the hydraulic conductivity via changes in soil moisture content as a result of transpiration.

c. Creation of gross void volume defects such as pipes and conduits that pass or partially penetrate through a levee as a result of lateral root growth followed by decay.

113. Standard techniques are available to construct 2-D flow nets and determine hydraulic head distribution in earthen embankments. Permeability discontinuities and unusual embankment geometries complicate the analysis, but these techniques are adequate to investigate Items a. and b. cited above. An iterative, finite difference approach using an engineering spreadsheet was adopted for this purpose in the present study.

114. Suitable techniques are not presently available, on the other hand, to construct 3-D flow nets which are required to investigate Item c., namely, the influence of void volume defects or macropores in a pervious levee. In principle, an iterative, finite difference approach that links together spreadsheets in the third dimension could be developed. A total of six flow inputs, as opposed to four in the 2-D case, would be required at interior grid or nodal points in such an analysis.

Iterative finite difference solution

115. Steady state seepage flow through an earthen levee must satisfy the equation governing the distribution of hydraulic potential, viz., the LaPlace equation, at every point. The finite difference method essentially consists of subdividing the flow region into a series of nodes or grid points and determining the appropriate finite difference equation for the hydraulic head at each point. The head at each point can be expressed in terms of the heads at surrounding or adjoining nodal points. Typical nodal relationships or rules for calculating the head at interior nodes, nodes adjacent to or on a boundary, and nodes on an interface between material of different permeability, are summarized in Figure 50.

116. These equations can be solved simultaneously by an iterative relaxation technique (Kleiner 1985; Das 1983) using an engineering spreadsheet. The spreadsheet program EXCEL was used for this purpose in the present study. Calculated values of the hydraulic head at the node points were in turn used to plot the equipotential lines by means of an isopotential or contour plotting program.

Influence of entrance, discharge, and transfer conditions

117. The orientation of the phreatic surface in unconfined seepage through an embankment or levee depends upon a number of factors. The influence of entrance, discharge, and interface transfer conditions relevant to seepage flow through a levee are summarized in Figure 51.

118. The effect of a permeability discontinuity upon the change in direction of phreatic surface at the interface depends upon both the permeability ratio (K_1/K_2) and the orientation of the interface (W) as shown in Figure 51. The direction of the line of seepage must satisfy the Forcheimer relationship, viz.,

$$\frac{Tan\ (A)}{Tan\ (B)} = \frac{K_2}{K_1} \qquad (2)$$

where: A and B are angles of incidence and departure, respectively, of the seepage line with respect to the interface. In addition to the Forcheimer relationship, the direction of the line of seepage must also satisfy the condition B = 270 - A - W for the cases noted in Figure 51.

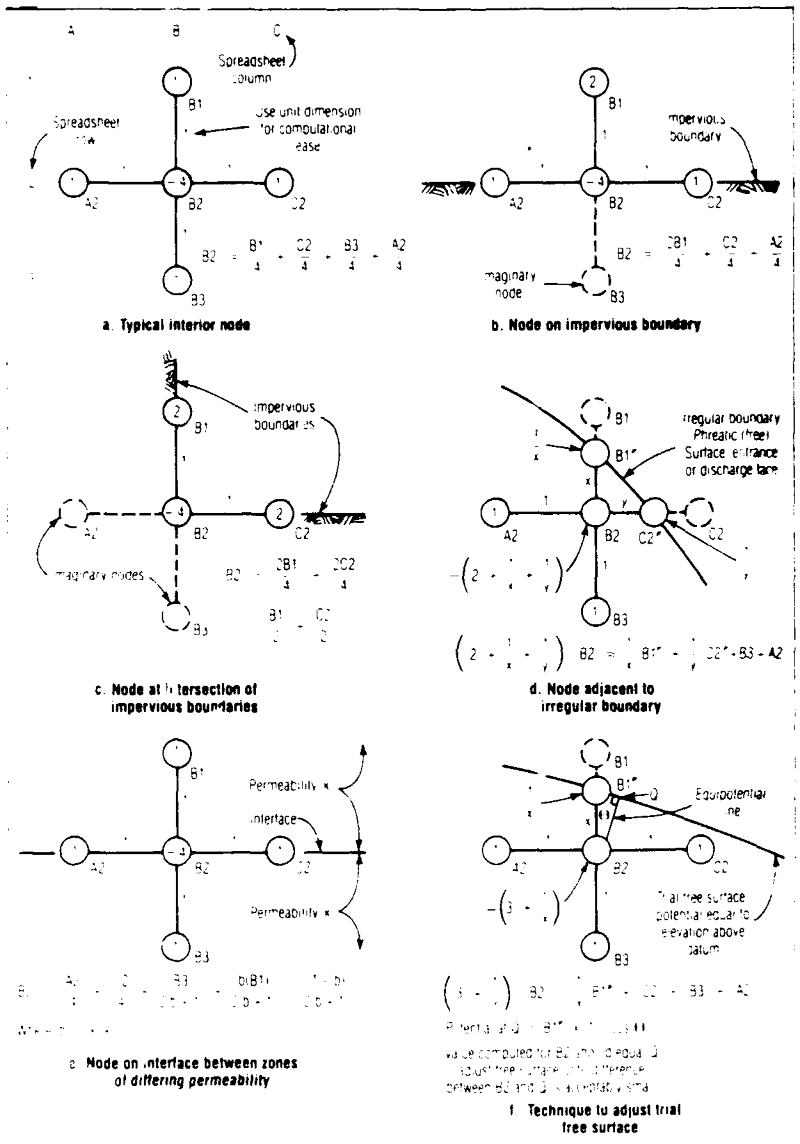


Figure 50. Summary of typical hydraulic head relationships for interior nodes, nodes adjacent to or on a boundary, and nodes on an interface between materials of different permeability (after Kleiner, 1985)

Equilibrium hydraulic head distributions

119. Standardized levee geometry. A standardized levee profile or geometry was adopted for the seepage analyses, as shown in Figure 52. The same side slopes and crest width specified in the standard levee sections shown in Figures 17 through 20 were retained for the seepage analyses. The embankment height was set at 20 ft. A 20-ft levee height with the use of 1-ft nodal spacings facilitated calculations in the seepage simulation. The actual

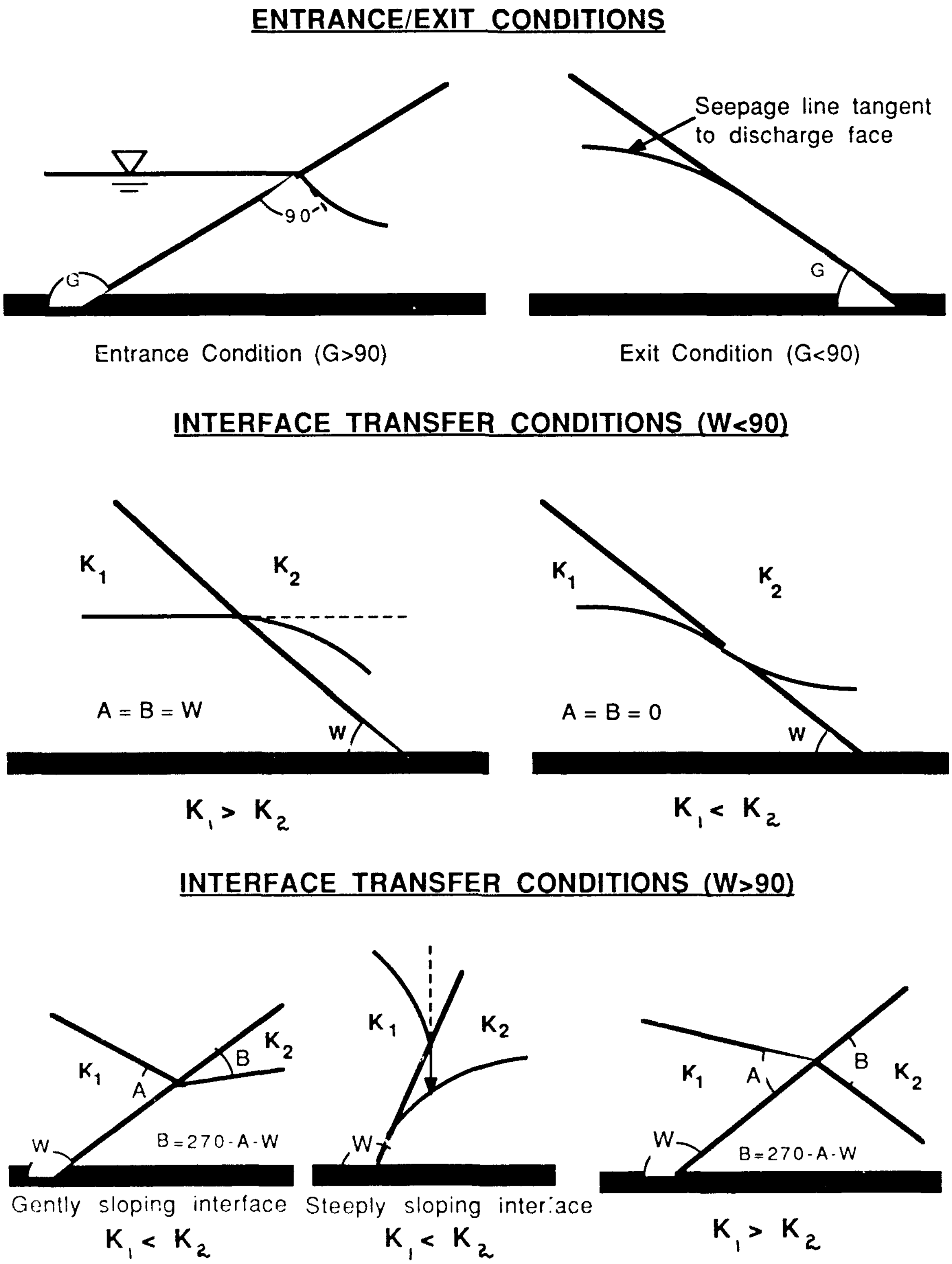


Figure 51. Entrance, discharge, and transfer conditions for phreatic surface during seepage flow through a levee

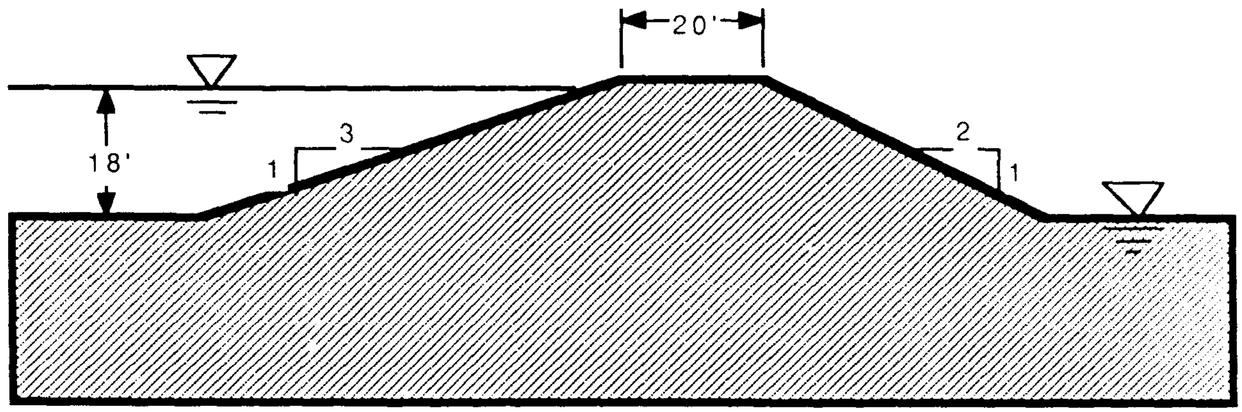


Figure 52. Standardized geometry adopted for seepage and stability analyses

levee dimensions (height) are less important if the main purpose of the seepage analysis is to compare behavior with and without a modified surface layer or skin.

120. The free water level on the channel or riverward side was set at 90 percent of the levee height for the seepage analyses. This level insured that the equilibrium phreatic surface intersected the landward face of the levee, and represents "worst case" scenario conditions.

121. <u>Homogeneous cross section.</u> Hydraulic head distributions for a homogeneous levee cross section were calculated on a spreadsheet using evenly spaced nodes with the iterative, finite difference method described previously. The phreatic surface or line of seepage was located with the aid of the rules and relationships shown in Figure 51 and according to procedures originally recommended by Casagrande (1938). The upstream face of the levee, up to its intersection with the free water surface, is considered an equipotential surface with a hydraulic head of 18 ft in the seepage analyses. This equipotential surface extends along the horizontal upstream boundary in front of the riverward toe of the levee. The discharge face of the levee, below the emergence point of the phreatic surface, is also treated as an equipotential surface with a hydraulic head value of zero. This equipotential surface likewise extends along the horizontal downstream boundary beyond the landward toe of the levee.

122. The spreadsheet output was converted to a data file that was used as the input to a contour or isopotential plotting program. The resulting equipotential map is shown in Figure 53 together with the location of the phreatic surface and the free water surface.

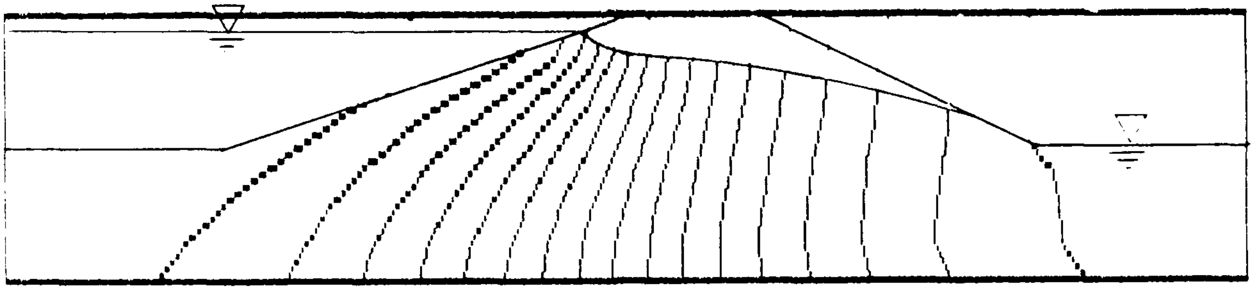


Figure 53. Equipotential lines and hydraulic head distribution for a homogeneous levee cross section

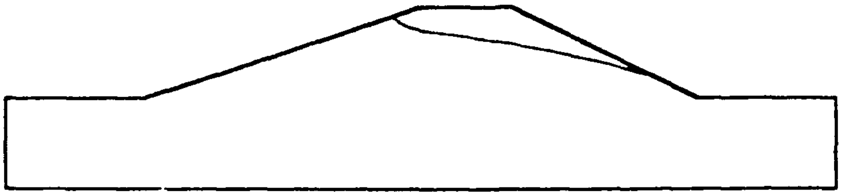
Composite levee with
modified surface layer

123. The impact of a modified surface layer or "skin" on either the riverward or landward slope with a different hydraulic conductivity (K_1) than the central core of the levee (K_2) was modelled by replacing the surface of a homogeneous levee with a 1-ft-thick modified layer. Most of the root biomass of plants is located very close to the surface, as shown in Figures 35 to 38.

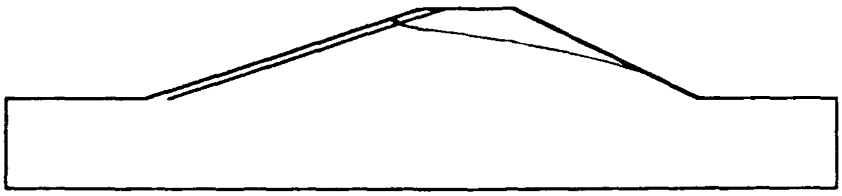
124. The first task was to determine the influence of a surface layer or skin on the location of the phreatic surface as shown schematically in Figure 54. This was accomplished by following the transfer condition rules summarized earlier in Figure 51. The "skin" was assumed to be either more or less permeable than the core by a factor of 10. The subsequent influence on the location and orientation of the phreatic surface as a result of this permeability contrast is depicted schematically in Figure 55.

125. The location of the phreatic surface is not greatly influenced by a modified surface on the upstream slope. Nor are the consequences of the change very significant. This is not the case, however, on the downstream side. A less permeable layer elevates the phreatic surface and increases the area of discharge on the downstream face whereas a more permeable layer depresses the phreatic surface and lowers the emergence point relative to the homogeneous case. A detailed view showing the influence of a permeability contrast between a surface layer and core at the upstream and downstream faces, respectively, is presented in Figure 55.

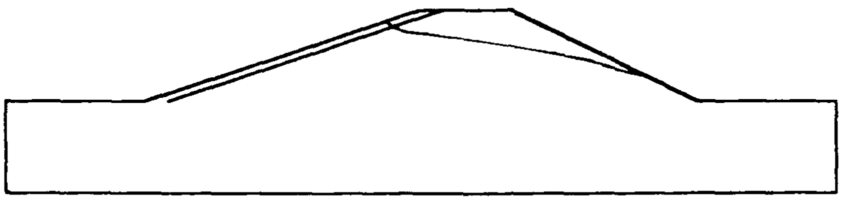
126. The spreadsheet program EXCEL was again used to obtain the hydraulic head distribution for a levee with a modified surface layer or skin with a different permeability. The resulting equipotential lines and hydraulic head distribution for the two cases of "more" and "less" permeable skin, respectively, are plotted and compared with the results for the homogeneous case in



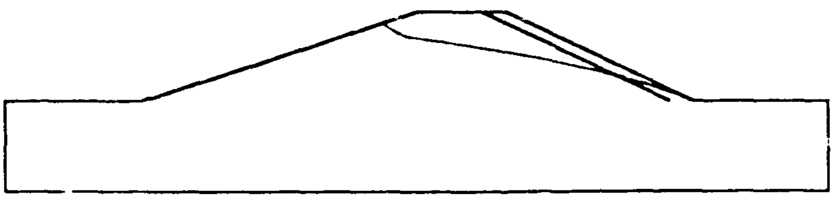
a) levee with constant permeability , k_2



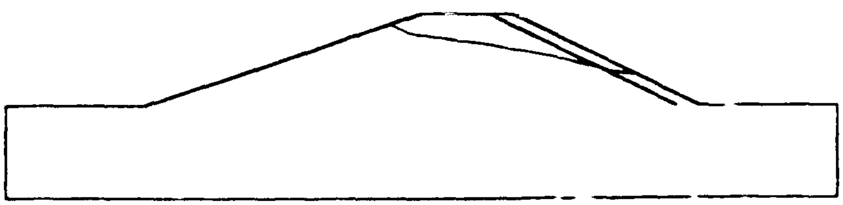
b) levee with a 1-ft layer of permeability , k_1 and $k_1 / k_2 = 10$



c) levee with a 1-ft layer of permeability , k_1 and $k_1 / k_2 = 0.1$



d) levee with 1-ft layer of permeability , k_1 and $k_1 / k_2 = 10$



e) levee with 1-ft layer of permeability , k_1 and $k_1 / k_2 = 0.1$

Figure 54. Schematic illustration showing influence of a modified surface permeability on the line of seepage

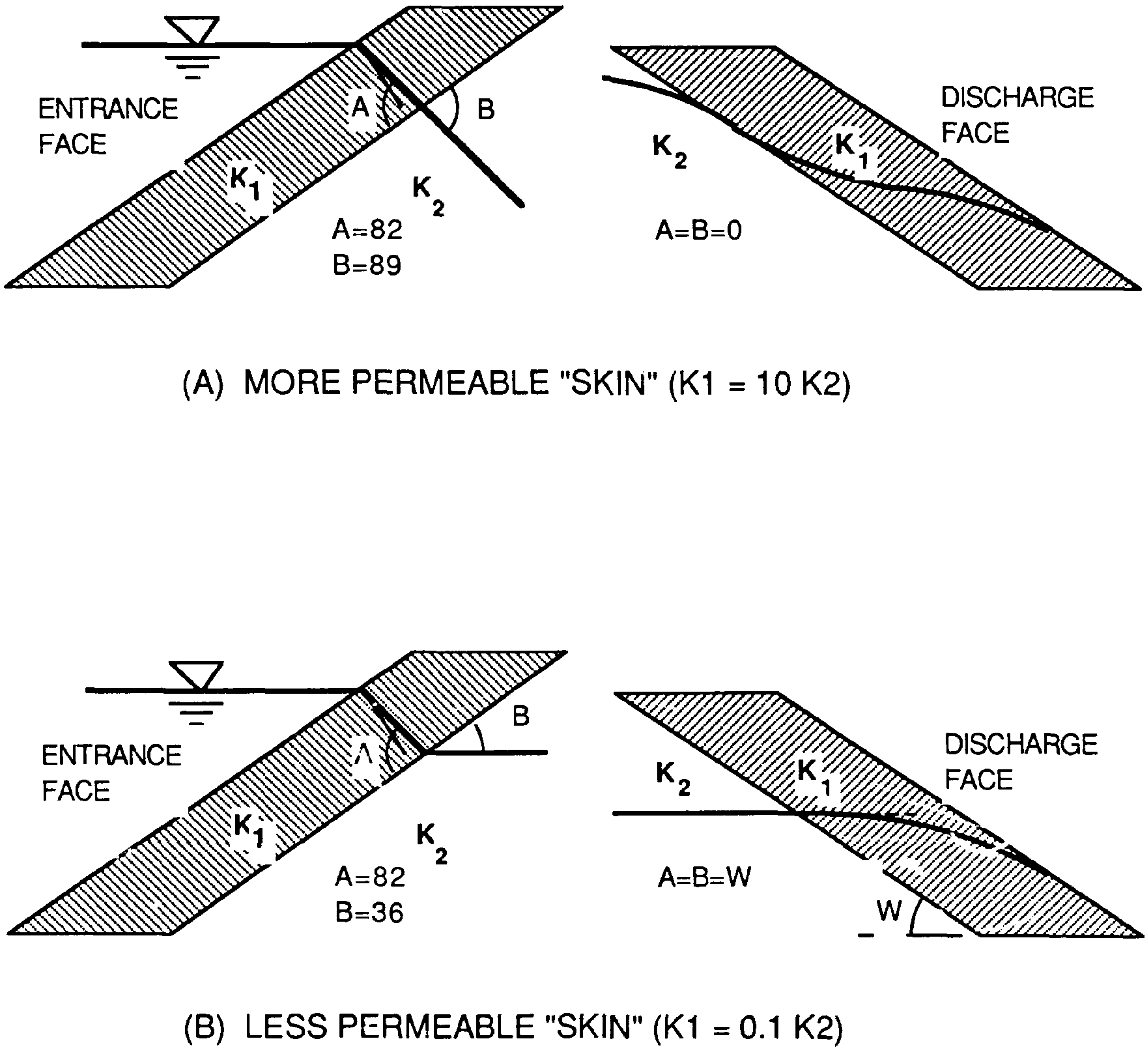
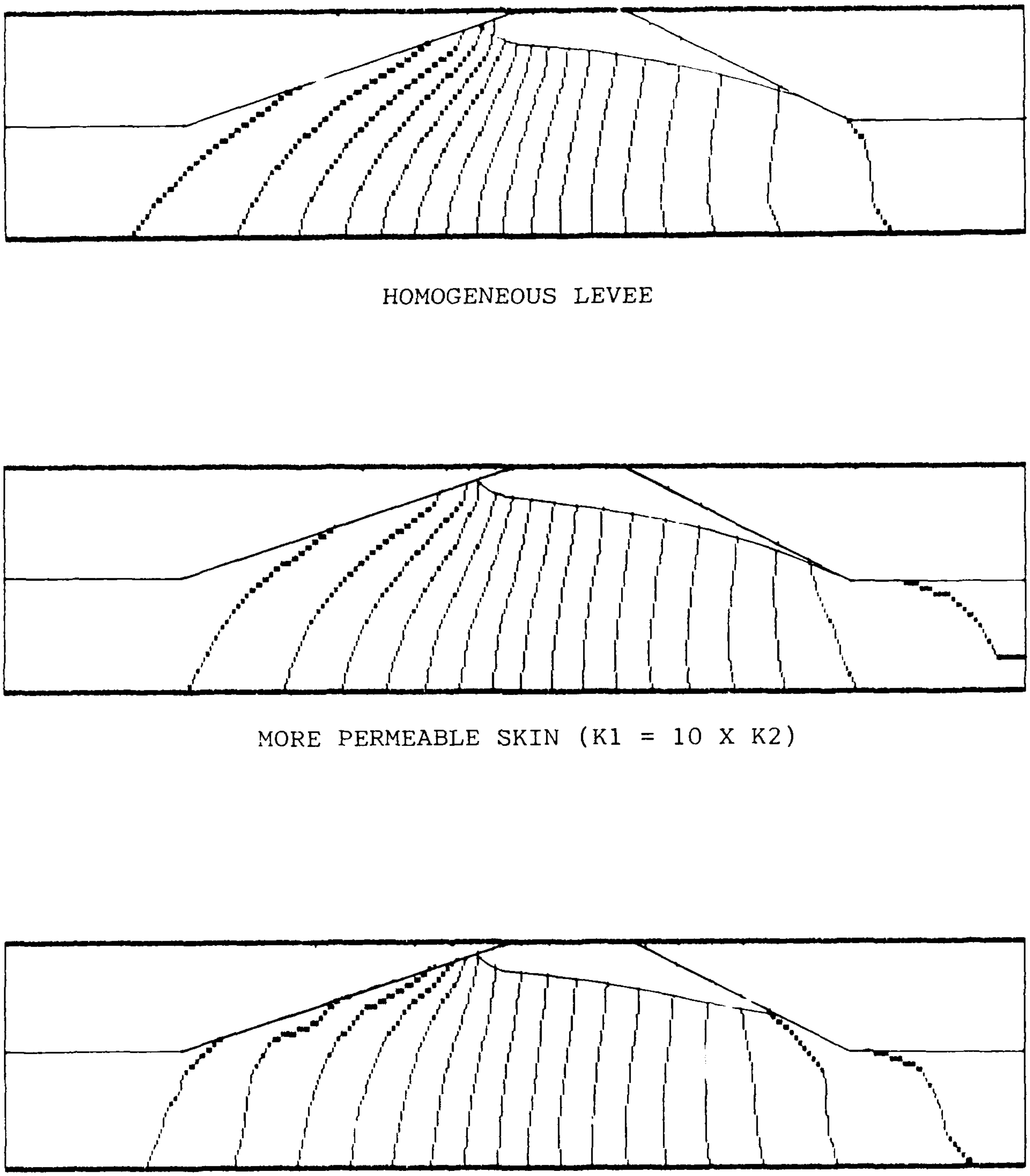


Figure 55. Influence of permeability contrast between facing or "skin" and core of levee on line of seepage

Figure 56. The following tentative conclusions can be drawn from the results of the comparison shown in Figure 56:

- a. A less permeable skin elevates the phreatic surface and increases the discharge area or seepage zone on the downstream face.
- b. A less permeable skin results in considerably higher exit gradients (closely spaced equipotential lines) at the discharge face near the toe.

127. Some distortion of the equipotential lines resulted from the relative coarseness of the grid or nodal spacing used in the spreadsheet analysis. A nodal spacing of 1 ft was used in the present study. The fidelity of the equipotential lines and hydraulic head distribution could be improved by using



HOMOGENEOUS LEVEE

MORE PERMEABLE SKIN (K1 = 10 X K2)

LESS PERMEABLE SKIN (K1 = 0.1 X K2)

Figure 56. Equipotential lines and hydraulic head distribution for homogenous levee and levees with a surface layer having a different permeability on the landward face

more closely spaced nodal points or more cells in the spreadsheet. This improvement can be achieved, however, only at considerable expense in computing time due to the large number of iterations required for an equilibrium solution.

Unsteady state flow

128. Both the seepage and stability analyses described herein are based upon steady seepage. In other words, it was assumed that elevated free water levels (FWL) on the channel side would be present for sufficiently long times to develop an equilibrium phreatic surface. Furthermore, the FWL in the channel was purposely set high in the analyses so that the phreatic surface or line of seepage would intersect the downstream face of the levee above the toe. The FWL was set at 80 to 90 percent of the levee crest elevation in both the seepage and mass stability analyses. Both these conditions, i.e., assumed level and duration, are part of a worst case scenario that may never occur in practice.

129. Flood stage duration records for the reach of levee in question along the Sacramento River indicate that (a) the peak flood levels have not risen more than 6-7 ft above the base of the levee, and (b) the duration of the near peak levels is not more than a few hours. A typical flood stage duration record is shown in Figure 57.

130. Huang (1986) has presented a simple method for locating the unsteady state or transient phreatic surfaces in an earth dam or levee. The phreatic surface progresses over time from the upstream to downstream face, with the upper end fixed at the pool (free water) elevation and the lower end moving along the base of the levee. Huang derived an equation to predict the distance (x) from the heel of the levee as a function of time (t). A plot of dimensionless distance (x/h) versus dimensionless time (T) is shown in Figure 58. The dimensionless time T is defined as follows:

$$T = (k\ t)/(n_e\ h) \qquad (3)$$

where

k = hydraulic conductivity, ft/min

t = elapsed time, min

n_e = effective porosity

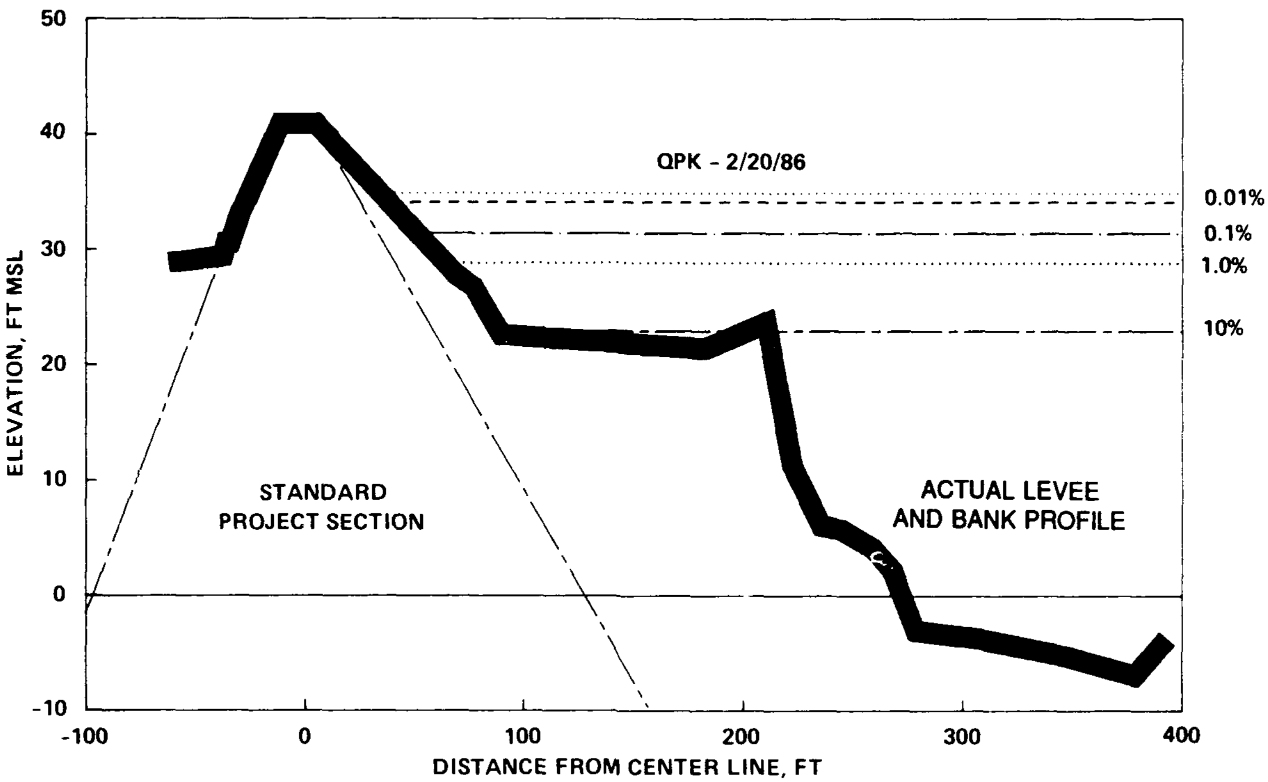


Figure 57. Typical flood-duration record for a levee site, Sacramento River channel levee (percentages represent the amount of time during the 1986 winter period during which these stages were equalled or exceeded, based on daily discharge values and supplemented by hourly values for the 1986 flood above 0.1 percent)

h = free water elevation above base of levee, ft

131. At any given time, t , the distance x can be determined from Figure 58 and the phreatic surface locatcd. The relationship in Figure 58 is, strictly speaking, only valid for cases involving an upstream slope of 2:1 and an impervious horizontal base. Flatter slopes can be handled using a procedure described by Huang, and the presence of a permeable foundation beneath the levee leads to conservative estimates.

132. Huang's method was used to plot the location of the transient phreatic surfaces fo. both a "low" (6-ft) and "high" (12-ft) flood stage. The results are shown in Figure 59. The time required for the phreatic surface to reach the toe of the levee under a low and high flood, respectively, are approximately 20 and 12 hr. Accordingly, not only are actual, maximum FWLs less than those assumed in the analyses described herein, they are also of

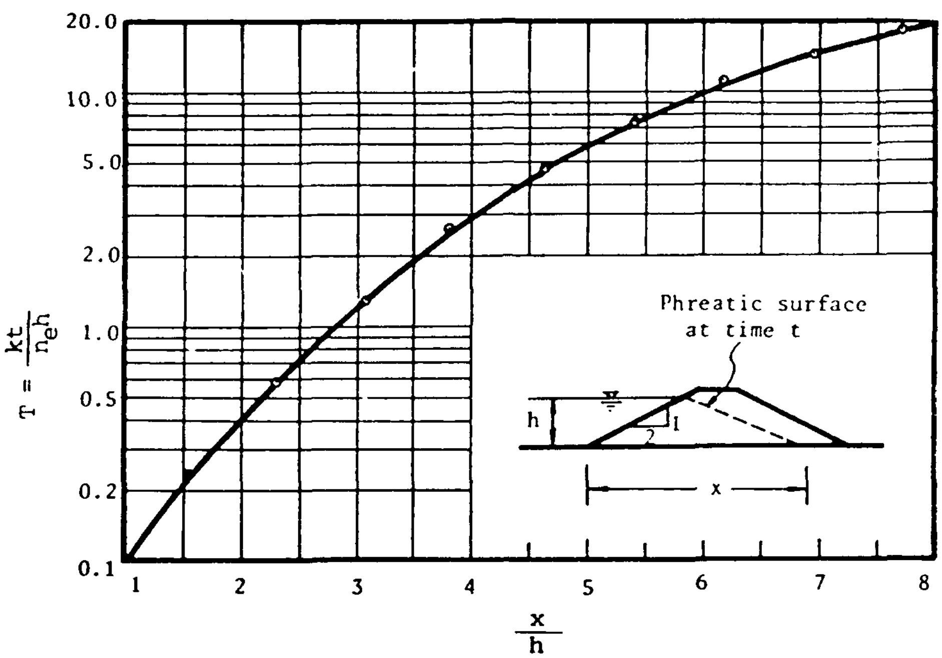


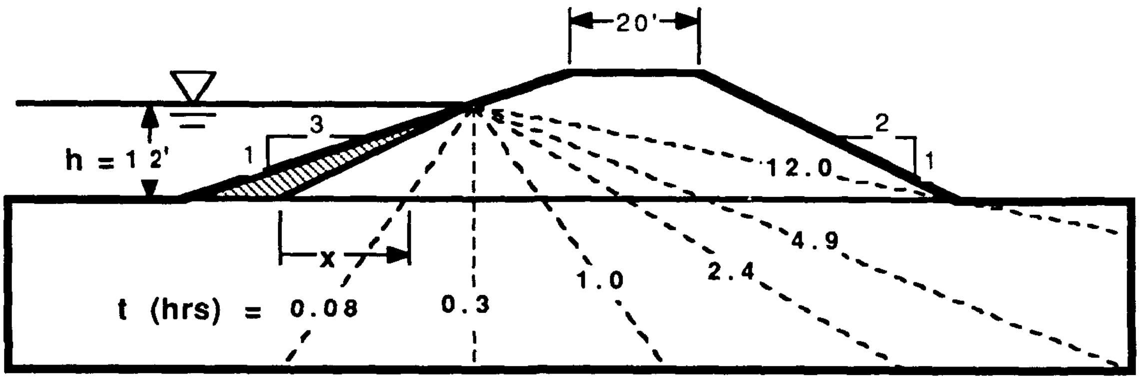
Figure 58. Plot of dimensionless time (T) versus dimensionless distance (x/h) for determining location of transient phreatic surface (from Huang 1986)

insufficient duration to develop an equilibrium phreatic surface under normal conditions, i.e., a levee having a relatively homogeneous cross section consisting of a uniform, medium sand with a hydraulic conductivity of 0.05 cm/sec measured at an average dry density of 90 pcf. The same conclusion would not hold for other conditions such as a vastly different average hydraulic conductivity or the demonstrable presence of gross hydraulic nonhomogeneities, e.g., a greatly modified surface layer (e.g., K1 >> K2) or conduits/pipes which penetrate through the levee. Little or no evidence was observed in the present field study to indicate that vegetation growing on the levee led to either of the latter conditions.

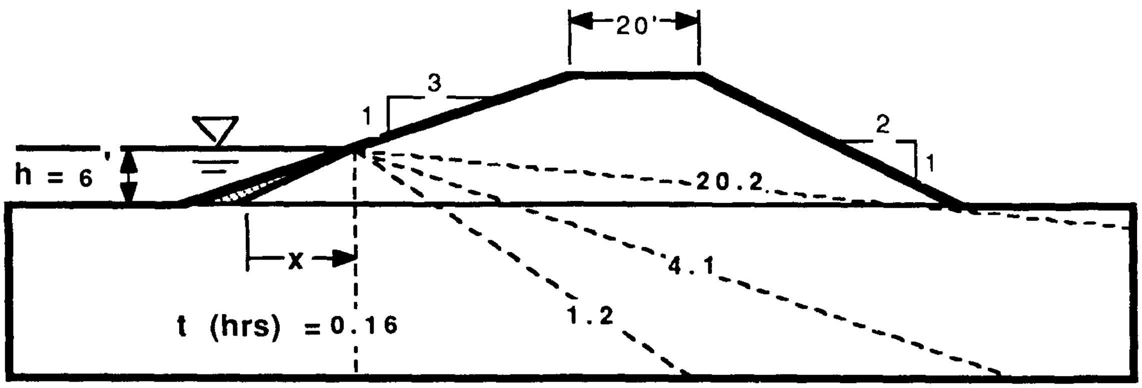
Mass Stability Analyses

General considerations

133. The relative security or factor of safety of an earthen slope is normally expressed as the ratio of the shear strength to the shear stress along a critical surface. A slope fails when the shear stress on this critical surface exceeds the shear strength.



(A) HIGH FLOOD STAGE - 12 FT ABOVE BASE OF LEVEE



(A) LOW FLOOD STAGE - 6 FT ABOVE BASE OF LEVEE

Figure 59. Development of transient phreatic surfaces with time in a sandy levee for two different flood stage elevations (assumed permeability = 0.05 cm/sec)

134. The type of failure (slide or flow) and failure mechanism (planar or rotational movement) depends upon a number of soil, slope, and hydrologic variables. Different types of mass stability analyses have been developed (see Huang 1983) to predict the factor of safety. These analyses take into account the influence of these variables.

135. The so-called <u>infinite slope</u> model is appropriate for analyzing planar slides in which the failure surface is planar and parallel to the slope over most of its length. The infinite slope model is generally applicable for sandy slopes subject to shallow sloughing and for slopes in which stratigraphic or geologic controls restrict sliding to a plane of weakness parallel

to the slope, e.g., a colluvial soil layer overlying an inclined bedrock contact.

136. A circular arc analysis is appropriate to rotational sides in which the failure surface is curved and can be modelled by the arc of a circle. Uniform clay slopes generally fail by deep-seated movement along a curved surface. More sandy slopes, on the other hand, tend to fail along shallow curved surfaces passing through the toe of the slope.

137. Both types of failure models, infinite slope and circular arc, are depicted schematically in Figure 60. In the case of a levee embankment or dam, both the upstream and downstream slopes are vulnerable to a mass stability failure. The upstream slope can fail as a result of rapid drawdown, e.g., a rapidly subsiding flood crest, and the downstream slope as a result of steady seepage (either parallel to or emerging from the face of the levee).

138. The stability of the levee described herein was determined for both the steady seepage and drawdown cases, respectively. Both infinite slope and circular arc analyses were employed. The influence of vegetation was investigated by introducing a thin surface layer or skin with different shear strength properties as a result of root permeation and modification of the soil.

Effect of plant roots
on soil shear strength

139. The main effect of the presence of fibers (roots) in a soil, insofar as shear strength is concerned, is to provide a measure of apparent cohesion. This fiber or root cohesion can make a significant difference in the resistance to shallow sliding or shear displacement in sandy soils with little or no intrinsic cohesion.

140. A number of studies have been reported in the technical literature on the contribution of woody roots to increased shear strength or root cohesion (c_R). Results and findings of these studies are summarized in Table 6. Contributions to increased shear strength can be estimated from either root biomass concentrations or from RARs. Actual shear tests in the laboratory and field on root/fiber permeated sands (Ziemer 1981; Gray and Ohashi 1983) indicate a shear strength increase per unit fiber concentration ranging from 7.4 to 8.7 psi/lb root/cf soil. This translates into an average value of 3.2 psi/percent RAR (assuming a root unit weight of 40 pcf).

141. RAR-versus-depth curves shown in Figure 38 for the elderberry site were used to estimate the likely root cohesion (c_R) as a function of depth.

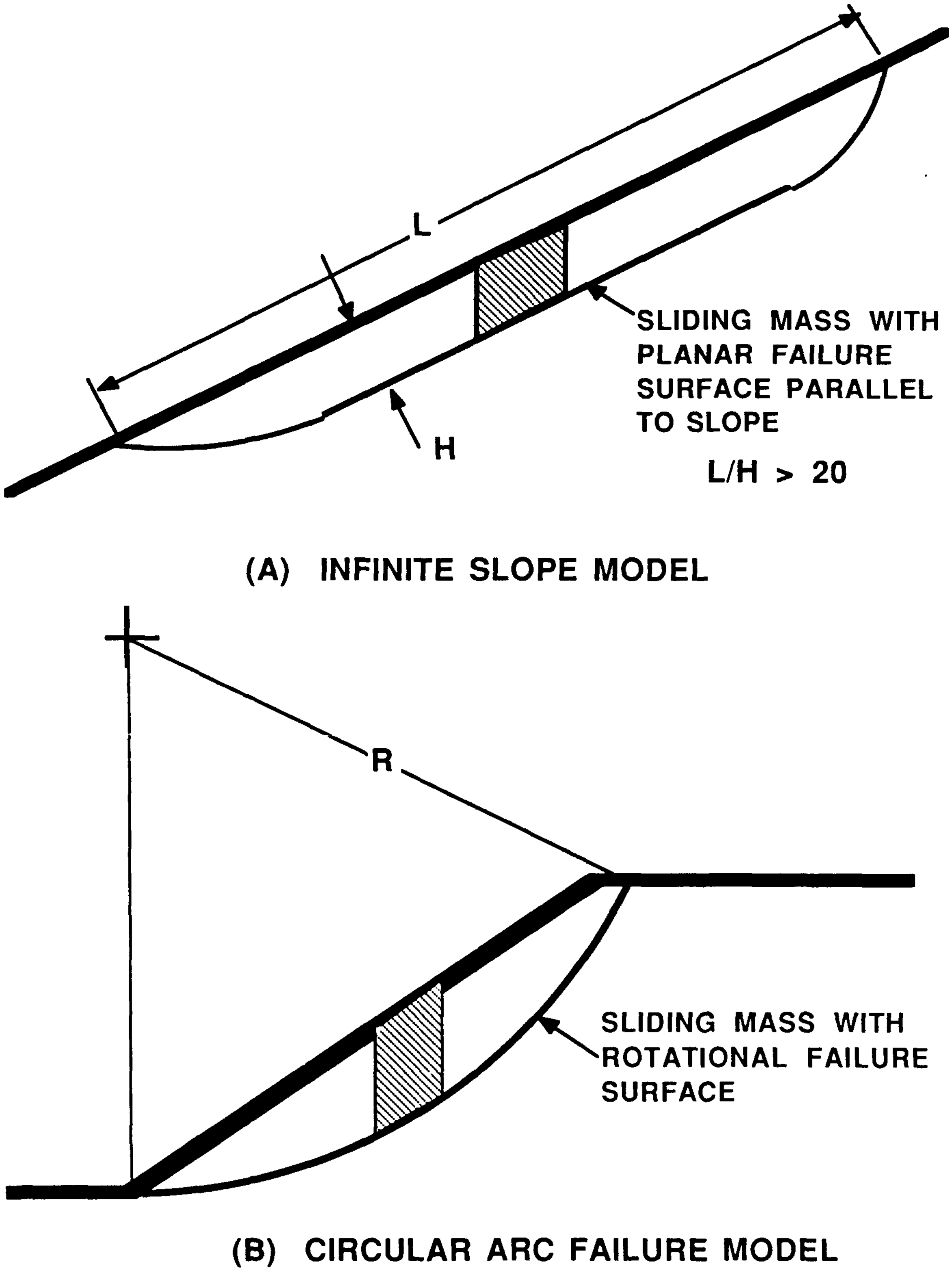


Figure 60. Slope failure models for mass stability analysis ((a) = infinite slope model; (b) = circular arc model)

TABLE 6. SUMMARY OF ROOT/FIBER CONTRIBUTIONS TO SOIL SHEAR STRENGTH

FIBER OR ROOT SYSTEM	MAXIMUM FIBER OR ROOT BIOMASS CONC			SHEAR STRENGTH INCREASE PER UNIT FIBER CONC.		MAX SHEAR STRENGTH INCR MEASURED IN TESTS		REFERENCE
	AREA RATIO (%)	WT. CONC. (= 40 PCF) lbs root / cf soil	kg root / cu m soil	PSI / lb/cf	kPa / kg/cu m	(PSI)	(kPa)	
HORIZONTAL SURFACE, VERTICAL ROOTS:								
Tree roots (spruce, hemlock) Horizontal shear surface, silty sand (interface between "B" and "C" Horizons) Live roots <13 mm diameter In-situ analysis	0.037	0.015	0.24	57.3	24.6	0.86	5.9	Wu, 1976
Tree roots (sugar maple) Horizontal shear surface, silty clay colluvium (interface between colluvium/bedrock) Live roots <25 mm diameter In-situ analysis	0.025	0.010	0.16	83.0	35.7	0.83	5.7	Riestenberg et al., 1983
Grass roots In-situ direct shear tests	0.050	0.020	0.33	34.8	15.0	0.70	5.0	CIRIA, 1987
AVERAGES:	0.037	0.015	0.24	58.4	25.1	0.80	5.5	
VERTICAL SURFACE, LATERAL ROOTS:								
Tree roots (Rocky Mtn. Douglas fir) Vertical surface, sandy loam Live roots <10 mm diameter In-situ analysis	0.046	0.018	0.29	68.9	29.6	1.24	8.6	Burroughs & Thomas, 1977
Tree roots (pinus contorta) Vertical shear surface, coastal sand Liver roots <17 mm diameter In-situ direct shear test	[illegible]	0.312	5.00	7.4	3.2	2.32	16.0	Ziemer, 1981
AVERAGES:	0.413	0.165	2.65	38.2	16.4	1.78	12.3	
LAB TESTS ON FIBER PERMEATED SANDS:								
Reed fibers (phragmites communis) Natural fibers: diameter = 2.0 mm Uniform sand Direct shear test	1.700	0.680	10.90	8.7	3.7	5.90	40.3	Gray & Ohashi, 1983
OVERALL AVERAGES	0.440	0.176	2.82	43.4	18.6	2.0	13.6	

The perpendicular transect data were used as representative of a "high" root concentration and the parallel transect, a "low" root concentration. These root concentrations and corresponding root cohesions were used in the stability analyses to investigate the likely influence of levee vegetation on the mass stability of a sandy levee with the properties and characteristics described previously.

Infinite slope analyses

142. Infinite slope analyses were conducted on both the upstream (3:1) slope and downstream (2:1) slope. Factors of safety were computed as a function of vertical depth (H) and seepage direction (θ) with respect to a horizontal plane. The static factor of safety is given by the following relationships (Huang 1983):

$$F = A\ [Tan(\phi)/Tan(\beta)]\ +\ B\,[(c + c_R)/\gamma H)] \qquad (4a)$$

$$A = [1 - r_u/Cos^2(\beta)] \qquad (4b)$$

$$B = [1/Cos^2(\beta)\,Tan(\beta)] \qquad (4c)$$

$$r_u = [\gamma/\gamma_w)\ \{1/(1 + Tan(\beta)\,Tan(\theta)\}] \qquad (4d)$$

where: ϕ = angle of internal friction

β = slope angle

c = soil cohesion

c_R = root cohesion

γ = soil density

γ_w = density of water

143. The infinite slope equation was programmed into a spreadsheet. The results of the analyses are tabulated in Tables 7 and 8 for a 2:1 slope and different assumed values of soil friction (ϕ), and amounts of root cohesion (c_R). Root cohesion was computed as a function of RAR which, in turn, varied with depth as explained in the previous section. The intrinsic soil

TABLE 7. EFFECT OF PLANT ROOTS ON STABILITY AGAINST SLOUGHING (SHALLOW FACE SLIDING) IN LEVEE SLOPES AS A RESULT OF SEEPAGE OR SUDDEN DRAWDOWN (2:1 SLOPE, PHI = 36 DEG)

2:1 SLOPE (26.6 DEG)
NO ROOTS (Ar/A = 0)

DEPTH TO FAILURE SURFACE H (FT)	SATD SOIL DENSITY ((PCF)	SOIL COHESION C (PSI)	SOIL FRICTION ANGLE ϕ (DEG)	ROOT COHESION Cr (PSI)	FACTOR OF SAFETY FOR VARIOUS SEEPAGE DIRECTIONS - THETA				
					THETA = 0 (DEG)	THETA = 26.6 (DEG)	THETA = 30 (DEG)	THETA = 60 (DEG)	THETA = 90 (DEG)
0.5	118	0	36	0	0.49	0.68	0.71	0.94	1.46
1.0	118	0	36	0	0.49	0.68	0.71	0.94	1.46
1.5	118	0	36	0	0.49	0.68	0.71	0.94	1.46
2.0	118	0	36	0	0.49	0.68	0.71	0.94	1.46
2.5	118	0	36	0	0.49	0.68	0.71	0.94	1.46
3.0	118	0	36	0	0.49	0.68	0.71	0.94	1.46
3.5	118	0	36	0	0.49	0.68	0.71	0.94	1.46
4.0	118	0	36	0	0.49	0.68	0.71	0.94	1.46

2:1 SLOPE (26.6 DEG)
LOW ROOT CONC (Ar/A = 0.1333 - 0.03 x H)

DEPTH TO FAILURE SURFACE H (FT)	SATD SOIL DENSITY ((PCF)	SOIL COHESION C (PSI)	SOIL FRICTION ANGLE ϕ (DEG)	ROOT COHESION Cr (PSI)	FACTOR OF SAFETY FOR VARIOUS SEEPAGE DIRECTIONS - THETA				
					THETA = 0 (DEG)	THETA = 26.6 (DEG)	THETA = 30 (DEG)	THETA = 60 (DEG)	THETA = 90 (DEG)
0.5	118	0	36	0.38	2.80	3.00	3.02	3.25	3.78
1.0	118	0	36	0.33	1.50	1.70	1.72	1.95	2.47
1.5	118	0	36	0.28	1.07	1.26	1.29	1.52	2.04
2.0	118	0	36	0.23	0.85	1.05	1.07	1.30	1.82
2.5	118	0	36	0.19	0.72	0.92	0.94	1.17	1.69
3.0	118	0	36	0.14	0.64	0.83	0.85	1.08	1.61
3.5	118	0	36	0.09	0.57	0.77	0.79	1.02	1.55
4.0	118	0	36	0.04	0.53	0.72	0.74	0.98	1.50

TABLE 7 (CONTINUED)

2:1 SLOPE (26.6 DEG)
HIGH ROOT CONC (Ar/A = 1.1746 X 10^(-0.3696 x H))

DEPTH TO FAILURE SURFACE H (FT)	SATD SOIL DENSITY ((PCF)	SOIL COHESION C (PSI)	SOIL FRICTION ANGLE ϕ (DEG)	ROOT COHESION Cr (PSI)	FACTOR OF SAFETY FOR VARIOUS SEEPAGE DIRECTIONS - THETA				
					THETA = 0 (DEG)	THETA = 26.6 (DEG)	THETA = 30 (DEG)	THETA = 60 (DEG)	THETA = 90 (DEG)
			1	2		3			
0.5	118	0	36	2.46	15.48	15.67	15.70	15.93	16.45
1.0	118	0	36	1.60	5.39	5.58	5.61	5.84	6.36
1.5	118	0	36	1.05	2.63	2.82	2.84	3.08	3.60
2.0	118	0	36	0.69	1.54	1.73	1.76	1.99	2.51
2.5	118	0	36	0.45	1.04	1.23	1.26	1.49	2.01
3.0	118	0	36	0.29	0.79	0.99	1.01	1.24	1.76
3.5	118	0	36	0.19	0.66	0.85	0.88	1.11	1.63
4.0	118	0	36	0.12	0.59	0.78	0.81	1.04	1.56

NOTES:

1. ϕ (deg) = 36 - 3.82 x C (psi). Correlation from levee BHS test results

2. Cr (psi) = 3.2 (Ar/A) (%). Correlation based on direct shear tests on *root/fiber/* soil composites (Gray & Ohashi, 1983; Ziemer 1981)

3. Seepage parallel to slope and "sudden drawdown" cases

TABLE 8. EFFECT OF PLANT ROOTS ON STABILITY AGAINST SLOUGHING (SHALLOW FACE SLIDING) IN LEVEE SLOPES AS A RESULT OF SEEPAGE OR SUDDEN DRAWDOWN(2:1 SLOPE, PHI = 28 DEG)

2:1 SLOPE (26.6 DEG)
NO ROOTS (Ar/A = 0)

DEPTH TO FAILURE SURFACE H (FT)	SATD SOIL DENSITY ((PCF)	SOIL COHESION C (PSI)	SOIL FRICTION ANGLE ∅ (DEG)	ROOT COHESION Cr (PSI)	FACTOR OF SAFETY FOR VARIOUS SEEPAGE DIRECTIONS - THETA				
					THETA = 0 (DEG)	THETA = 26.6 (DEG)	THETA = 30 (DEG)	THETA = 60 (DEG)	THETA = 90 (DEG)
0.5	118	0	28	0	0.36	0.50	0.52	0.69	1.07
1.0	118	0	28	0	0.36	0.50	0.52	0.69	1.07
1.5	118	0	28	0	0.36	0.50	0.52	0.69	1.07
2.0	118	0	28	0	0.36	0.50	0.52	0.69	1.07
2.5	118	0	28	0	0.36	0.50	0.52	0.69	1.07
3.0	118	0	28	0	0.36	0.50	0.52	0.69	1.07
3.5	118	0	28	0	0.36	0.50	0.52	0.69	1.07
4.0	118	0	28	0	0.36	0.50	0.52	0.69	1.07

2:1 SLOPE (26.6 DEG)
LOW ROOT CONC (Ar/A = 0.1333 - 0.03 x H)

DEPTH TO FAILURE SURFACE H (FT)	SATD SOIL DENSITY ((PCF)	SOIL COHESION C (PSI)	SOIL FRICTION ANGLE ∅ (DEG)	ROOT COHESION Cr (PSI)	FACTOR OF SAFETY FOR VARIOUS SEEPAGE DIRECTIONS - THETA				
					THETA = 0 (DEG)	THETA = 26.6 (DEG)	THETA = 30 (DEG)	THETA = 60 (DEG)	THETA = 90 (DEG)
0.5	118	0	28	0.38	2.67	2.81	2.83	3.00	3.38
1.0	118	0	28	0.33	1.37	1.51	1.53	1.70	2.08
1.5	118	0	28	0.28	0.94	1.08	1.09	1.26	1.65
2.0	118	0	28	0.23	0.72	0.86	0.88	1.05	1.43
2.5	118	0	28	0.19	0.59	0.73	0.75	0.92	1.30
3.0	118	0	28	0.14	0.50	0.64	0.66	0.83	1.21
3.5	118	0	28	0.09	0.44	0.58	0.60	0.77	1.15
4.0	118	0	28	0.04	0.39	0.54	0.55	0.72	1.11

TABLE 8 (CONTINUED)

2:1 SLOPE (26.6 DEG)
HIGH ROOT CONC (Ar/A = 1.1746 X 10^(-0.3696 x H))

DEPTH TO FAILURE SURFACE H (FT)	SATD SOIL DENSITY ((PCF)	SOIL COHESION C (PSI)	SOIL FRICTION ANGLE ∅ (DEG)	ROOT COHESION Cr (PSI)	FACTOR OF SAFETY FOR VARIOUS SEEPAGE DIRECTIONS - THETA				
					THETA = 0 (DEG)	THETA = 26.6 (DEG)	THETA = 30 (DEG)	THETA = 60 (DEG)	THETA = 90 (DEG)
			1	2		3			
0.5	118	0	28	2.46	15.35	15.49	15.50	15.67	16.06
1.0	118	0	28	1.60	5.26	5.40	5.42	5.59	5.97
1.5	118	0	28	1.05	2.49	2.64	2.65	2.82	3.21
2.0	118	0	28	0.69	1.41	1.55	1.57	1.74	2.12
2.5	118	0	28	0.45	0.91	1.05	1.07	1.24	1.62
3.0	118	0	28	0.29	0.66	0.80	0.82	0.99	1.37
3.5	118	0	28	0.19	0.53	0.67	0.69	0.86	1.24
4.0	118	0	28	0.12	0.46	0.60	0.62	0.79	1.17

NOTES:

1. "Worst case" scenario...minimum friction angle and negligible cohesion

2. Cr (psi) = 3.2 (Ar/A) (%). Correlation based on direct shear tests on root/fiber/ soil composites (Gray & Ohashi, 1983; Ziemer 1981)

3. Seepage parallel to slope and "sudden drawdown" cases

cohesion was assumed to be zero, and the friction angle set to either 36° (the maximum value measured on the levee) or 28° (the lowest recorded value). The latter represents a "worst-case" scenario, i.e., combination of lowest recorded friction coupled with absence of any cohesion. The average friction and cohesion values measured from in situ borehole shear tests were 31.6° and 1.16 psi, respectively.

144. Sudden drawdown in an infinite slope analysis is equivalent to saturated, steady seepage when the seepage direction is parallel to the slope, i.e., ($\theta = \beta$). A factor of safety for this condition was computed in every case.

145. Results from the spreadsheet analyses are presented graphically in Figures 61 through 64 for the case of soil friction angle equal to 36°. Factor of safety is plotted as a function of depth and seepage direction for the case of no root cohesion ($c_R = 0$) for the 2:1 and 3:1 slope, respectively, in Figures 61 and 62. The factor of safety drops below one when the seepage either parallels or emerges from the slope face for the 2:1 slope. The corresponding factor of safety for the case of low root concentrations is plotted in Figures 63 and 64. The factor of safety exceeds unity for all depths and seepage directions in this case (except for low seepage angle directions in the 2:1 slope).

146. The results show that both the seepage direction (θ) and presence of root cohesion (c_R) have a significant effect on the factor of safety. Even a small amount of root cohesion can increase the factor of safety substantially. This influence is very pronounced at shallow depths where root concentrations are highest and reinforcement effects, therefore, greatest. In this regard grass roots appear to be just as effective as tree and shrub (woody) roots because of their high concentration at shallow depths. The RARs measured at the control site, for example, exceeded all other sites at depths under 6 in. (see Figures 35 and 36) because of the abundance of grasses and herbaceous ground cover at this location. In the presence of root cohesion, even for low root concentrations, the factor of safety exceeds unity at all depths up to 2.0 ft even for worst case scenario conditions of low friction angle ($\phi = 28°$) and seepage emerging from the slope ($\vartheta = 0°$).

147. One effect of the roots is to displace the critical shear surface (surface where F = 1.0) downward. The further downward the critical surface is displaced, the less prone the slope is to surface sloughing or ravelling. If the critical surface is displaced too far, however, the infinite slope

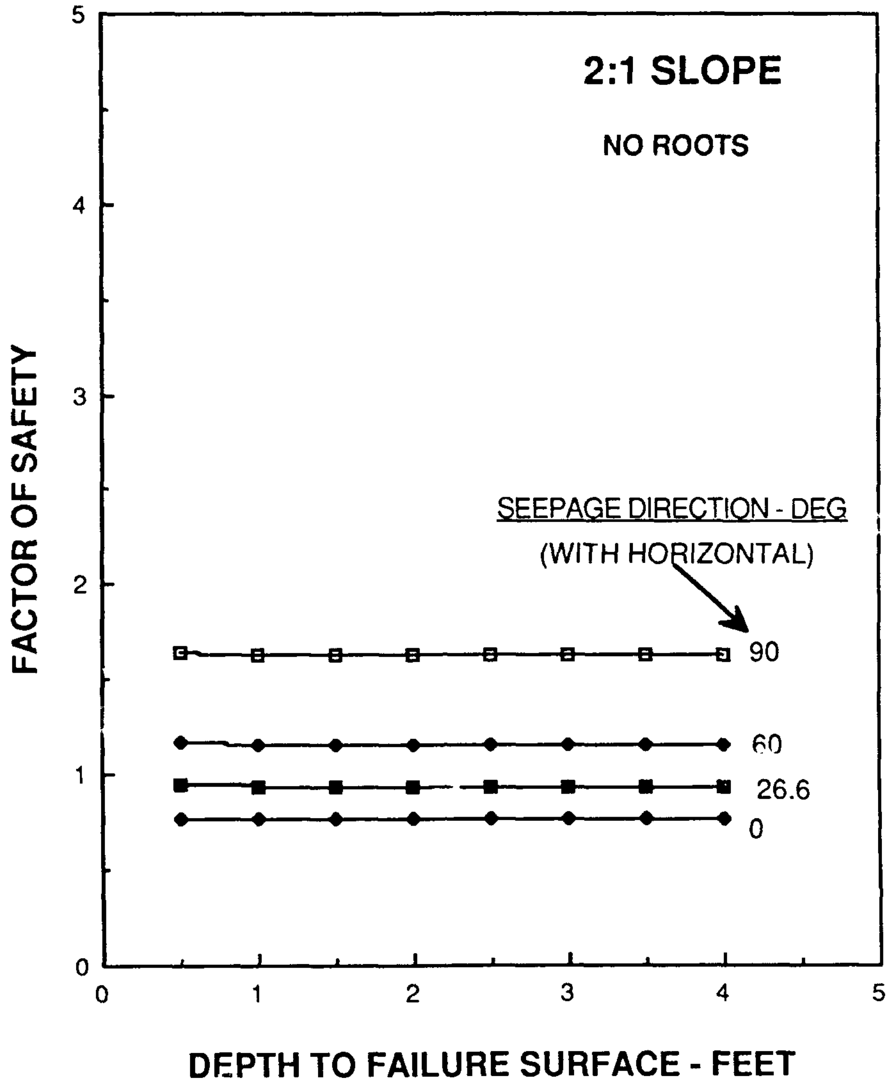


Figure 61. Infinite slope analysis of saturated (2:1) downstream slope of levee without roots (friction angle = 36°)

model is no longer valid. This analysis assumes that the length of the sliding mass is large relative to its thickness (L > 20 H) as shown in Figure 60. For a 15-ft-high sandy levee, this criteria translates to a thickness of 1.7 and 2.4 (or vertical depth to the sliding plane of 1.9 and 2.5) for 2:1 and 3:1 slopes, respectively. At sufficiently large depths (H > 4 ft) the root concentrations and reinforcement will decrease to zero. At these depths the sliding mass will not have the dimensions or aspect ratio required by the infinite slope model. When this condition is no longer observed, then another type of analysis, either a circular arc or log spiral failure analysis, should be used as well.

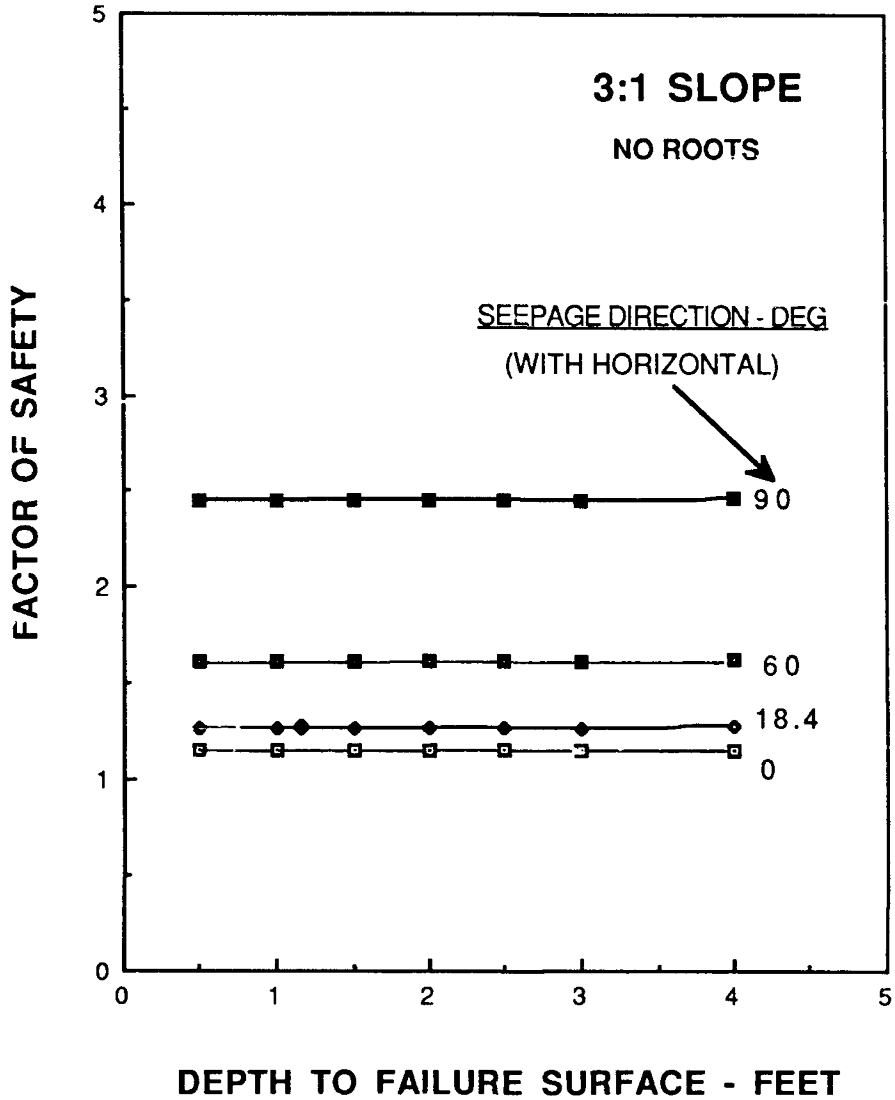


Figure 62. Infinite slope analysis of saturated (3:1) downstream slope of levee without roots (friction angle = 36°)

148. The effect of seepage direction (θ) on stability deserves some comment. Downward seepage (θ = 90°) greatly increases the factor of safety. This condition, in fact, yields the same factor of safety as a dry slope. Accordingly, to the extent that slope vegetation and plant roots promote downward seepage and infiltration, they also enhance stability.

Circular arc analyses

149. Curved failure surfaces in sandy slopes are log spiral shaped and pass through the toe of the slope. A circular arc analysis was used to simulate this failure condition. Critical circles in sandy slopes are generally

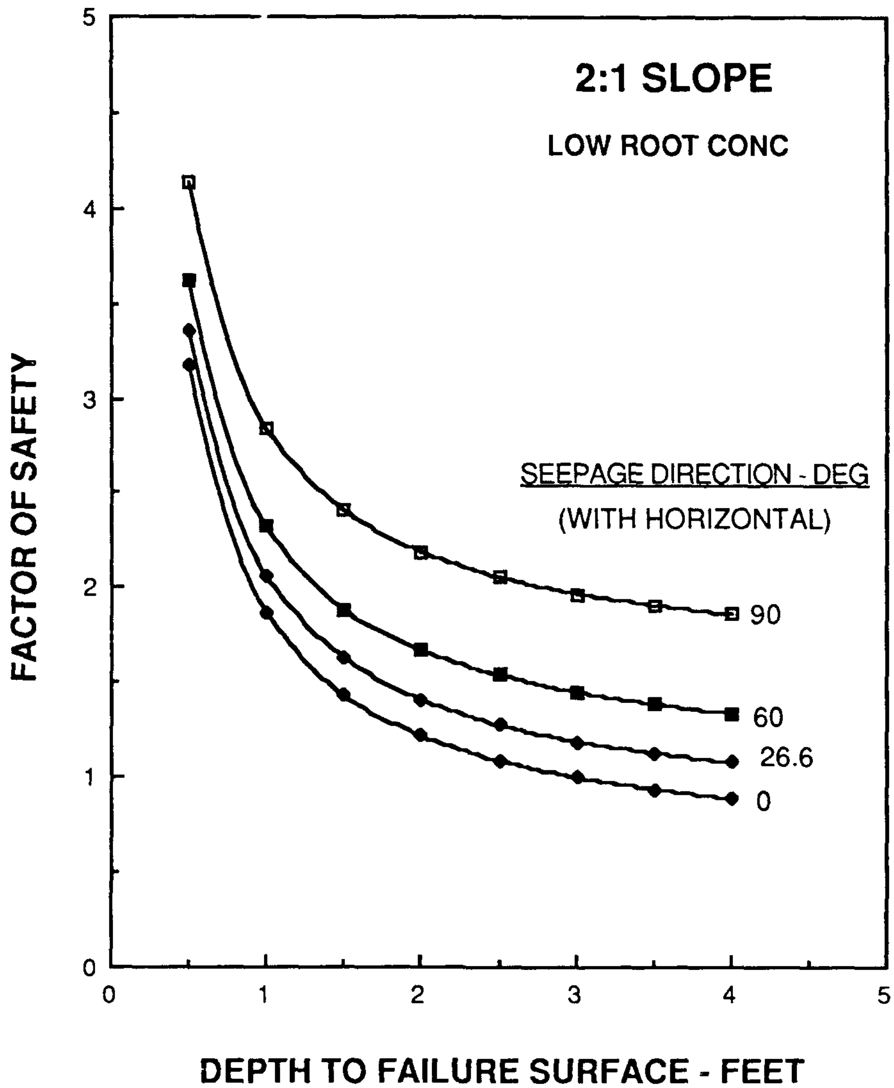


Figure 63. Infinite slope analysis of saturated (2:1) downstream slope of levee <u>with roots</u> (friction angle = 36°)

quite flat and shallow; this is one reason that the infinite slope model with its assumption of a planar failure surface is also a good approximation.

150. There are several variants of circular arc stability analyses. One approach is to subdivide the failure mass, defined by the intersection of a trial failure circle with the slope, into a series of vertical elements or "slices." The factor of safety against rotational sliding is determined by calculating the static force and moment equilibrium of the slices. The Modified (or Bishop) Method of slices was used in this study. This method assumes that the vertical forces of the sides of the slices are opposite and equal, which in turn means that the resultant of the side forces on a slice acts

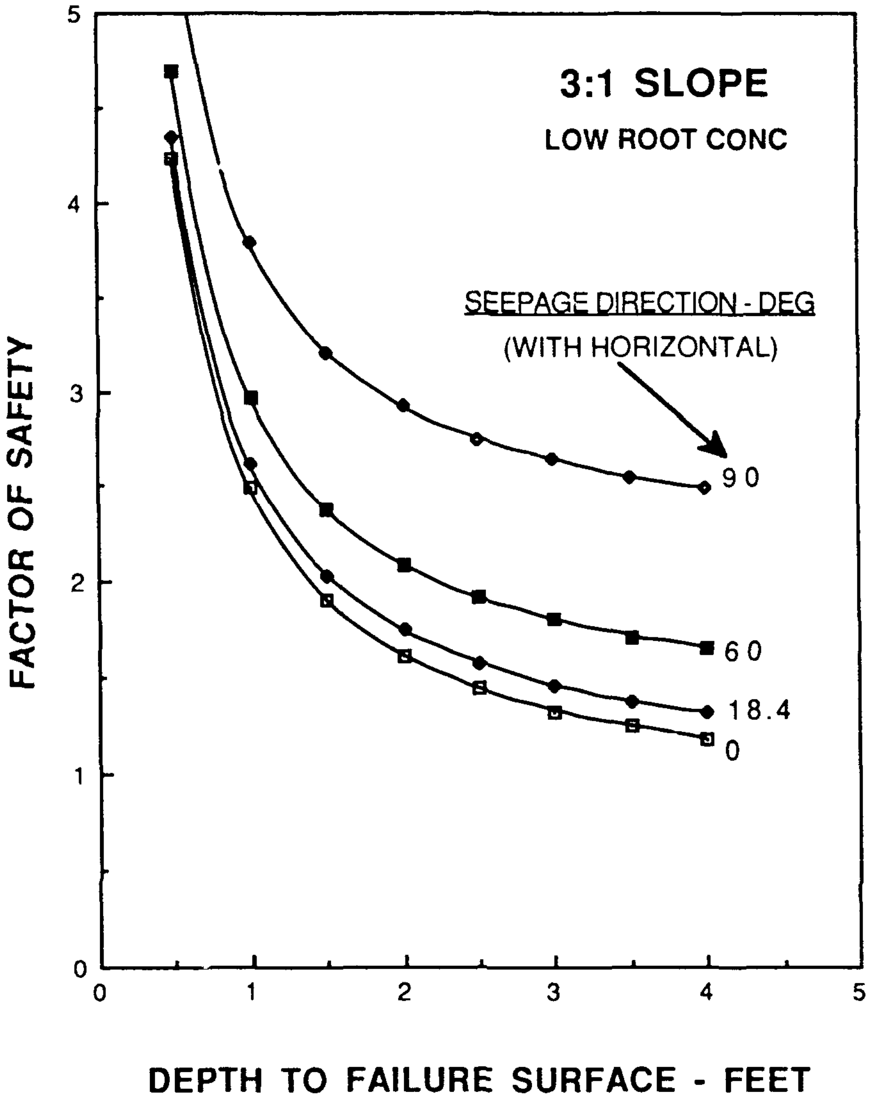


Figure 64. Infinite slope analysis of saturated (3:1) downstream slope of levee with roots (friction angle = 36°)

horizontally. The assumption of equal and opposite vertical side forces on the slices is reasonable if sufficiently narrow slides are used in the analysis.

151. The factor of safety computed by the Modified Method of slices is given by the following equation (Huang 1983):

$$F = \frac{\sum\left[\left\{-c'\Delta x + (W_i - u_i \Delta x_i)\right\} Tan\phi'\right](1/m_a)}{\sum W_i \; Sin\alpha_i} \qquad (5a)$$

$$m_a = [Cos\alpha \; \{1 + (1/F) \; (Tan\phi' Tan\alpha)\}] \quad (5b)$$

where: c', ϕ' = effective shear strength parameters

Δx_i = slice width

W_i = slice weight

u_i = pore water pressure at base of slice

α_i = inclination of base of a slice

152. This equation must be solved by iteration because the factor of safety (F) appears on both sides of the equation. The usual procedure is to select several trial circles until the critical circle with the lowest factor of safety is identified. The calculations are tedious and best performed on a high-speed computer. The program SB-SLOPE (distributed by VonGunten Engineering, Fort Collins, CO) was used for this purpose.

153. The factor of safety was computed for several trial circles for both steady seepage (2:1 slope) and sudden drawdown (3:1 slope) conditions, respectively, as shown in Figures 65 and 66. Successively deeper circles passing through the toe (or heel) were selected. The most critical circles were the shallow ones in both cases.

154. The influence of root cohesion was investigated by assigning a cohesion value as a function of depth as described in the previous section. Results of safety factor calculations for the steady seepage and sudden drawdown cases are shown graphically in Figures 67 and 68, respectively, for the same failure circles used previously in Figures 65 and 66. The thin soil layers (6 in. thick) shown in the cross-section diagram of the slope represent soils with different cohesion based on a "low" root concentration in the soil.

155. Results of the circular arc analysis show that in the unreinforced (no root) case, the critical failure circle ($F < 1$) is quite shallow. The presence of roots, even at low concentration, completely reverses this trend. Now the shallow circles (where root concentrations are highest) have the highest factor of safety, whereas the deeper circles are relatively unaffected. Since the deeper circles are not critical in the first place ($F > 1$), the influence of plant roots is less important.

Comparison of safety factors

156. Safety factors computed by the circular arc and infinite slope analyses, respectively, were compared for steady seepage and sudden drawdown

SB-SLOPE

Simplified Bishop Slope Stability Analysis

PROJECT: Stability Analysis of Downstream Face , w/o Roots

LOCATION: Sacramento River Channel Levee

ANALYSIS DONE ON FILE SSD3

FAILURE CIRCLES AND FACTORS OF SAFETY

No. 1	X= 134.7	Y= 45	R= 31.5	FS= 0.65
No. 2	X= 125.6	Y= 31.5	R= 16.6	FS= 0.79
No. 3	X= 124.9	Y= 33.8	R= 18.8	FS= 0.86
No. 4	X= 123.6	Y= 41.3	R= 26.4	FS= 0.98
No. 5	X= 122.4	Y= 47.5	R= 32.5	FS= 1.04

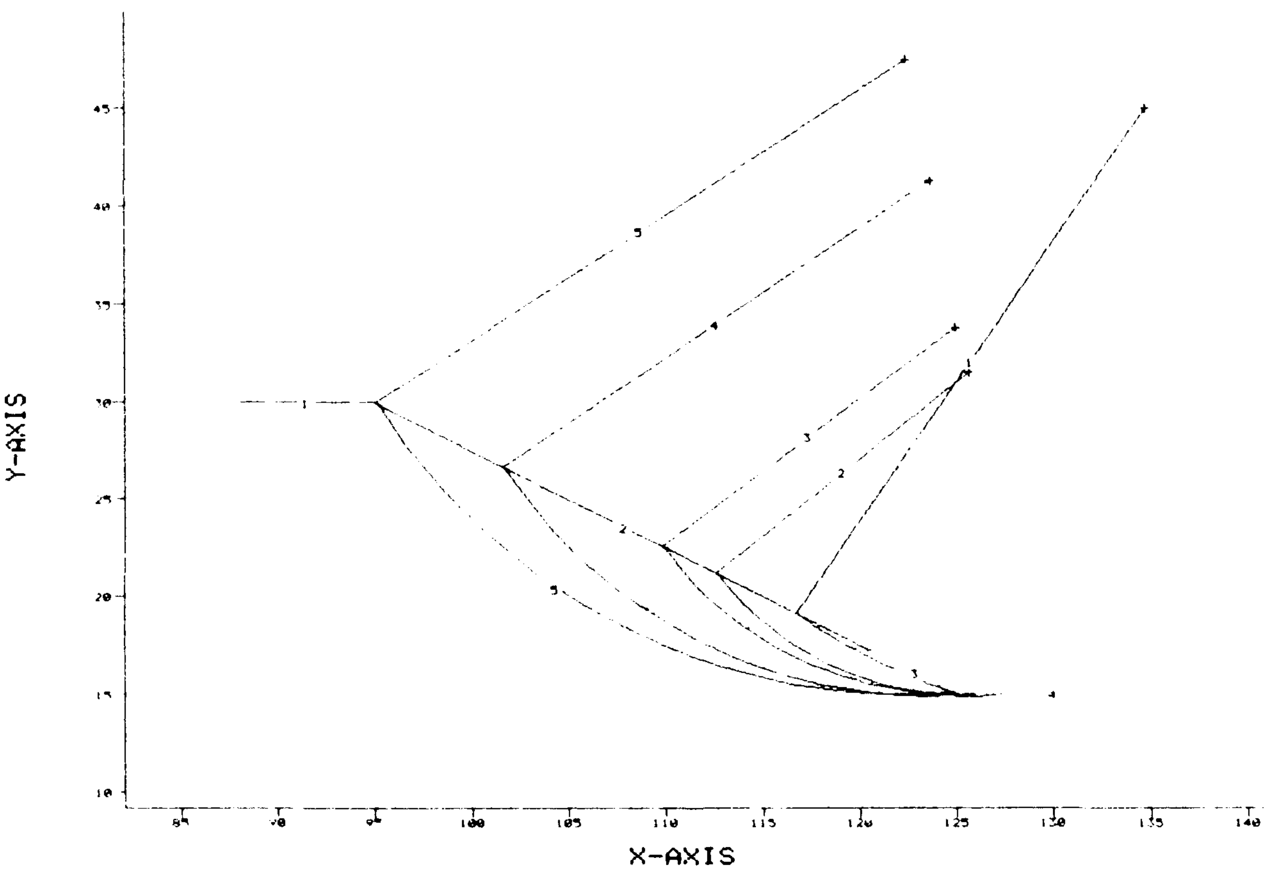


Figure 65. Circular arc stability analysis of (2:1) landward slope of levee under steady seepage conditions. No roots are present (friction angle = 30°)

SB-SLOPE

Simplified Bishop Slope Stability Analysis

PROJECT: Stability Analysis of Upstream Face , w/o Roots

LOCATION: Sacramento River Channel Levee

ANALYSIS DONE ON FILE SS1
FAILURE CIRCLES AND FACTORS OF SAFETY

No. 1	X= 30	Y= 23.9	R= 8.6	FS= 0.72
No. 2	X= 30	Y= 37.6	R= 22.3	FS= 0.72
No. 3	X= 30	Y= 51.1	R= 35.8	FS= 0.73
No. 4	X= 30	Y= 76.4	R= 61.4	FS= 0.74
No. 5	X= 30	Y= 83	R= 68.1	FS= 0.77

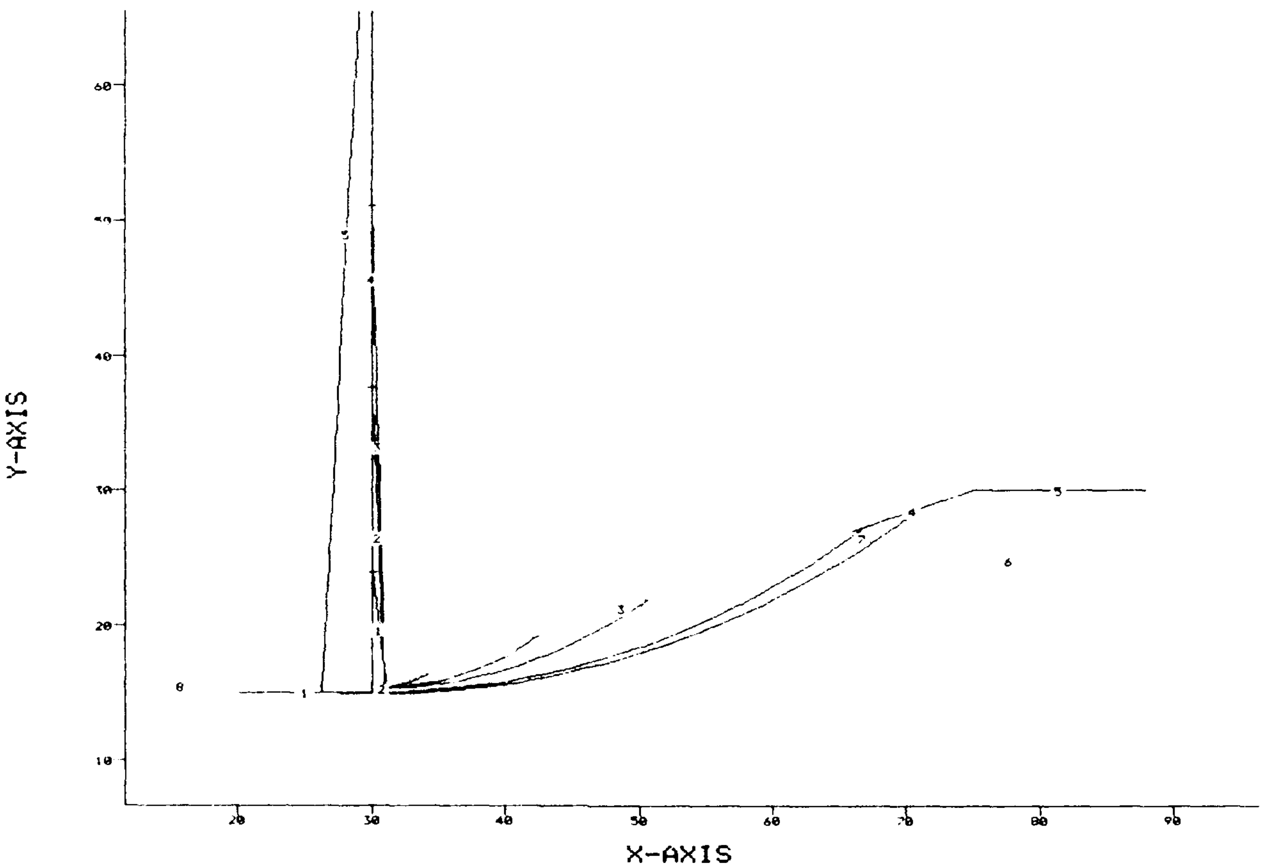


Figure 66. Circular arc stability analysis of (3:1) riverward slope of levee under sudden drawdown conditions. No roots are present (friction angle = 30°)

SB-SLOPE

Simplified Bishop Slope Stability Analysis

PROJECT: Stability Analysis of Downstream Face , with Roots

LOCATION: Sacramento River Channel Levee

ANALYSIS DONE ON FILE SSD3R
FAILURE CIRCLES AND FACTORS OF SAFETY

No. 1	X= 134.7	Y= 45	R= 31.5	FS= 5.57
No. 2	X= 125.6	Y= 31.5	R= 16.6	FS= 1.75
No. 3	X= 124.9	Y= 33.8	R= 18.8	FS= 1.54
No. 4	X= 123.6	Y= 41.3	R= 26.4	FS= 1.23
No. 5	X= 122.4	Y= 47.5	R= 32.5	FS= 1.16

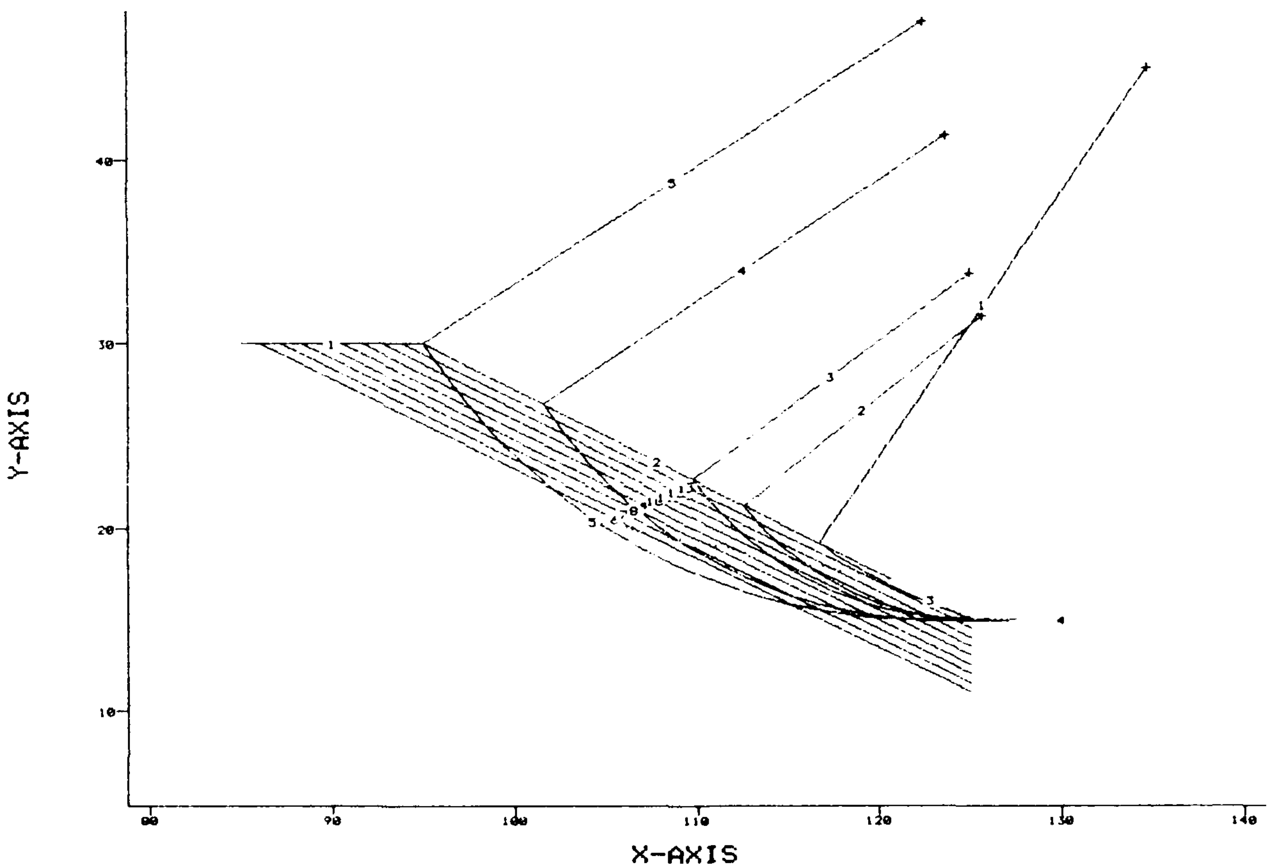


Figure 67. Circular arc stability analysis of (2:1) landward slope of levee under steady seepage conditions. Low root concentration (friction angle = 30°)

SB-SLOPE

Simplified Bishop Slope Stability Analysis

PROJECT: Stability Analysis of Upstream Face , with Roots

LOCATION: Sacramento River Channel Levee

ANALYSIS DONE ON FILE SS1R
FAILURE CIRCLES AND FACTORS OF SAFETY

No. 1	X= 30	Y= 23.9	R= 8.6	FS= 10.5
No. 2	X= 30	Y= 37.6	R= 22.3	FS= 3.40
No. 3	X= 30	Y= 51.1	R= 35.8	FS= 2.01
No. 4	X= 30	Y= 76.4	R= 61.4	FS= 1.16
No. 5	X= 30	Y= 83	R= 68.1	FS= 1.10

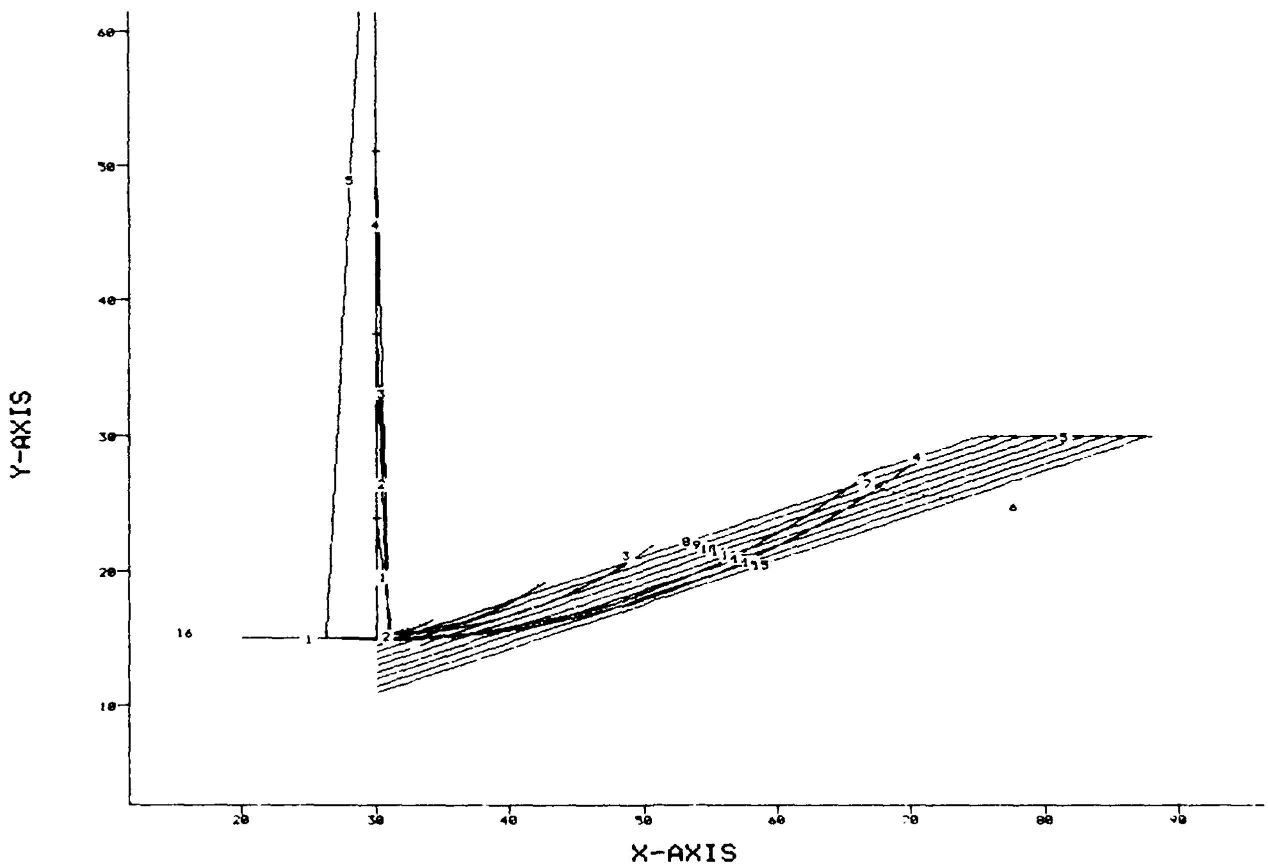


Figure 68. Circular arc stability analysis of (3:1) riverward slope of levee under sudden drawdown conditions. Low root concentration (friction angle = 30°)

conditions. The results of this comparison are shown in Tables 9 and 10 for both the "no root" and "low root" concentration cases, respectively. The presence of roots, even at low concentrations, more than doubles the critical factor of safety in both cases.

157. The circular arc analyses were conducted with ϕ = 30°, whereas the infinite slope analyses were run at 28° and 36° -- the minimum and maximum values measured in the borehole shear tests. The average friction angle for all tests was 31.6°. The agreement between circular arc and infinite slope analyses is excellent for the steady seepage case--both with and without root cohesion. Factors of safety computed by the circular arc analyses lie within the values computed by the infinite slope method for $28<\phi<36$ and $0<\theta<b$. Agreement between the two methods for the sudden drawdown case is less satisfactory, with the infinite slope method giving lower estimates.

TABLE 9. COMPARISON OF FACTORS OF SAFETY - NO ROOTS

METHOD OF ANALYSIS	FACTOR OF SAFETY	
	STEADY SEEPAGE (2:1 SLOPE)	SUDDEN DRAWDOWN (3:1 SLOPE)
CIRCULAR ARC: (CRITICAL CIRCLE) PHi = 30 DEG	0.65	0.72
INFINITE SLOPE:		
PHI = 36 DEG THETA = 0 DEG	0.76	N/A
THETA = BETA	0.94	1.27
PHI = 28 DEG THETA = 0 DEG	0.56	N/A
THETA = BETA	0.68	0.93

TABLE 10. COMPARISON OF FACTORS OF SAFETY - LOW ROOT CONCENTRATION, SHALLOW FAILURE SURFACE

METHOD OF ANALYSIS	FACTOR OF SAFETY	
	STEADY SEEPAGE (2:1 SLOPE)	SUDDEN DRAWDOWN (3:1 SLOPE)
CIRCULAR ARC: (SHALLOW CIRCLE, H = 1 FT) PHI = 30 DEG	1.75	3.4
INFINITE SLOPE: (H=1 FT)		
PHI = 36 DEG THETA = 0 DEG	1.87	N/A
THETA = BETA	2.00	2.62
PHI = 28 DEG THETA = 0 DEG	1.64	N/A
THETA = BETA	1.78	2.28

PART VI: SUMMARY AND CONCLUSIONS

Summary

158. Woody vegetation growing on the side slopes of levees modifies the top surface layer and this in turn can affect the hydraulic regime and stability of the levee. A field study was conducted to determine the distribution and concentration of roots, voids, and pedotubules along transects both perpendicular and parallel to the crest of a sandy levee. The results of the field study together with the findings of seepage and stability analyses described herein lead to the following conclusions:

Levee vegetation
composition and distribution

- a. An analysis of random vegetation transects showed that the dominant tree species growing on the 6-mile study reach of channel levee along the Sacramento River are valley oak (*Quercus lobata*) and cottonwood (*Populus fremontii*). Valley oak appeared well adapted to all levee environments and was the only arboreal species found growing on both landward and riverward slopes of the levee in addition to the levee crest.
- b. The principal shrub species were licorice (*Glyclyrrhiza* sp.), rose (*Rosa californica*), elderberry (*Sambucus* sp.), and willow (*Salix* sp.). Among the shrubs, licorice appeared to be particularly well adapted to all levee environments and vegetation management practices. This plant has an extensive root system and thrives on burning.
- c. Apart from valley oak, rose, and licorice, all other tree and shrub species were found on the riverward slope only.

Root distribution in
sandy channel levees

- a. The profile method was adapted successfully to determine the distribution and concentration of roots and biopores in a sandy channel levee.
- b. Lateral plant roots are restricted to and modify mainly the first few feet beneath the surface of a levee. Root area ratios did not exceed 2 percent and generally decreased approximately exponentially with depth. Most of the root biomass is concentrated in the top 2 ft.
- c. The only valley oak that was fully excavated had a deep, vertical, central tap root. Laterals radiating away from this central tap root tend to angle down sharply in order to reach moisture in a sandy, and hence droughty, levee. This root architecture means that lateral roots are much less likely to penetrate across or through a levee.

d. All tree/shrub species investigated had similar lateral root area ratio profiles. A comparison of root area ratios at different depth intervals indicated that no one species exhibited a higher root area ratio than another over the entire rooting depth. An exception was the "control" or grass and herbaceous ground cover site, which exhibited high root area ratios at very shallow depths (less than 6 in.).

Occurrence, probable cause, and
influence of voids and pedotubules

a. Voids and pedotubules (infilled holes or conduits) were mapped in the vertical faces of the trenches at each site. The average number of voids per unit area reached a maximum at a depth of 6 in. and then decreased with depth to a minimum value.

b. Voids or holes were created by burrowing animals or insects. Voids created by burrowing animals, namely the California ground squirrel, were easily identified by their size, shape, and form. These burrow holes occurred at all depths including one hole which was exposed at a depth of 4 ft.

c. No voids clearly attributable to plant roots were observed. Only rapidly formed holes of recent origin, namely, animal burrows or insect holes, are likely to be observed at any given instant. Root holes which form more slowly, as roots gradually decay, are more likely to evolve directly into pedotubules and not persist long as voids.

d. Pedotubules could be distinguished visually from the surrounding soil by differences in color and texture and in some cases by differences in gradation and density as well. These pedotubules appeared to form as a result of soil washed in during overbank flows or floods.

e. Unlike intact roots, open voids or conduits in a levee represent an immediate danger from the point of view of a piping or internal erosion failure. These features could affect internal stability as a result of high seepage velocities and gradients associated with them.

f. Other factors in addition to the presence of biopores are responsible for internal erosion or piping failure in a levee. The role of hydraulic fracturing, which can occur independently of the existence of such macropores, must be considered as well.

Influence of roots on hydraulic regime

a. The influence of a modified surface layer or skin (with a different hydraulic conductivity) on hydraulic head distribution and line of seepage was determined for both the case of a less- and more permeable skin. A less permeable skin resulted in enlargement of the exposed seepage area and greater exit gradients near the toe.

b. There was no evidence in the field study that vegetation affected the hydraulic conductivity one way or the other either by modification of microscopic or macroscopic porosity.

c. The results of a transient seepage analysis showed that the maximum flood of record was of insufficient magnitude, in stage elevation and/or duration, to cause the line of seepage or phreatic surface to reach the landward toe of a design levee with a homogenous cross section. The presence or absence of vegetation should not alter this conclusion provided the vegetation does not greatly change the hydraulic conductivity of the levee soils (see preceding conclusion).

d. A 3-D seepage analysis should be developed to study the influence of pipes or pedotubules that penetrate or partially penetrate through a levee. There was little or no evidence from limited excavation and trenching conducted during the field study itself to indicate that fully penetrating conduits actually exist.

Influence of roots on mass stability

a. Roots reinforce the soil and increase the shear strength in a measurable manner. A shear strength increase or root cohesion can be estimated from the root biomass per unit volume or alternatively from the RAR. A value of root cohesion (cR) of 3.2 psi/% RAR was calculated in the study. This root cohesion can greatly improve the mass stability, particularly in a sandy loam with little or no intrinsic cohesion.

b. Both infinite slope and circular arc stability analyses were performed on the landward and riverward slope for steady seepage and sudden drawdown conditions, respectively. These analyses showed that even low root concentrations as measured along selected transects in the sandy levee sufficed to make the slope more secure under "worst case" scenario conditions (i.e., high free water level, low shear strength, etc).

c. Results of the circular arc analyses show that in the unreinforced (no root) case the critical failure circles ($F < 1$) are quite shallow. The presence of roots, even at low concentrations, completely reversed this trend. Shallow circles (where root concentrations are highest) now have the highest factor of safety whereas deeper circles are relatively unaffected. Since the deeper circles are not critical in the first place ($F > 1$) the influence of plant roots is less important in this instance.

d. Grassed slopes exhibited relatively high root area ratios at very shallow depths (under 6 in.) compared to woody sites. Consequently, grass or herbaceous cover appears to be just as effective in preventing shallow sloughing or surface ravelling. Woody plants, on the other hand, are more deeply rooted and therefore more effective in preventing deeper seated sliding. Shrubs and bushes provide the benefits of woody roots without the possible liabilities associated with large trees such as wind-throwing.

Conclusions

159. Based on the results of preliminary field studies conducted on a sandy channel levee, it does not appear that woody vegetation adversely affects the structural integrity of a levee. No open voids or conduits clearly attributable to plant roots were observed. The presence of plant roots reinforced the soil and increased the shear strength of the surface layers in a measurable manner.

160. Grasses and herbaceous ground cover provided greater amounts of roots at very low depths (under 6 in.) than did woody plants. Consequently, this type of vegetation appears to be just as effective as woody plants in preventing shallow sloughing or surface ravelling. Woody roots, on the other hand, are stronger and tend to penetrate more deeply; therefore, they are more effective in preventing deeper seated slope failures. Low-lying shrubs and bushes provide the benefits of woody roots without possible liabilities associated with large trees growing on a levee.

161. The profile wall method and other techniques described in the report can be adapted successfully to determine the distribution and concentration of roots and biopores in a levee structure. These techniques should be used to investigate the effects of vegetation on other types of levees and in regions with different climatic conditions.

PART VII: RECOMMENDATIONS FOR FUTURE RESEARCH

162. As a result of the research described herein, the following topics have been identified as useful areas for future research:

<u>a</u>. Root architecture and distribution.

1. Conduct additional full excavations around trees to determine if vertical rooting is the predominant orientation in sandy levees. Very few large, lateral roots were exposed in the trench faces at the live oak site.

2. Conduct gravimetric root biomass assays in conjunction with the profile-wall surveys to see if the latter adequately accounts for the presence of root fibers less than 1 mm in diameter. The latter size class is probably underestimated in the profile-wall survey method.

<u>b</u>. Hydraulic studies.

1. Conduct in situ hydraulic conductivity testing with large, double ring infiltrometers in order to determine if near surface portions of a levee are modified by the presence of vegetation. Permeability/density tests on small volume samples do not adequately reflect macroscopic hydraulic properties of levee soils, i.e., the influence of large void volume defects such as animal burrows, pedotubules, root holes, etc.

2. Develop a 3-D seepage analysis technique to model adequately the effects of pipes, holes, large voids, etc., on the seepage regime and the danger of internal erosion.

<u>c</u>. General.

1. Conduct similar field studies in levees made of cohesive soils and compare results with those obtained for sandy levees.

2. Conduct studies in regions where climatic conditions are more humid and the vegetation spectrum is different from the semi-arid conditions of central California.

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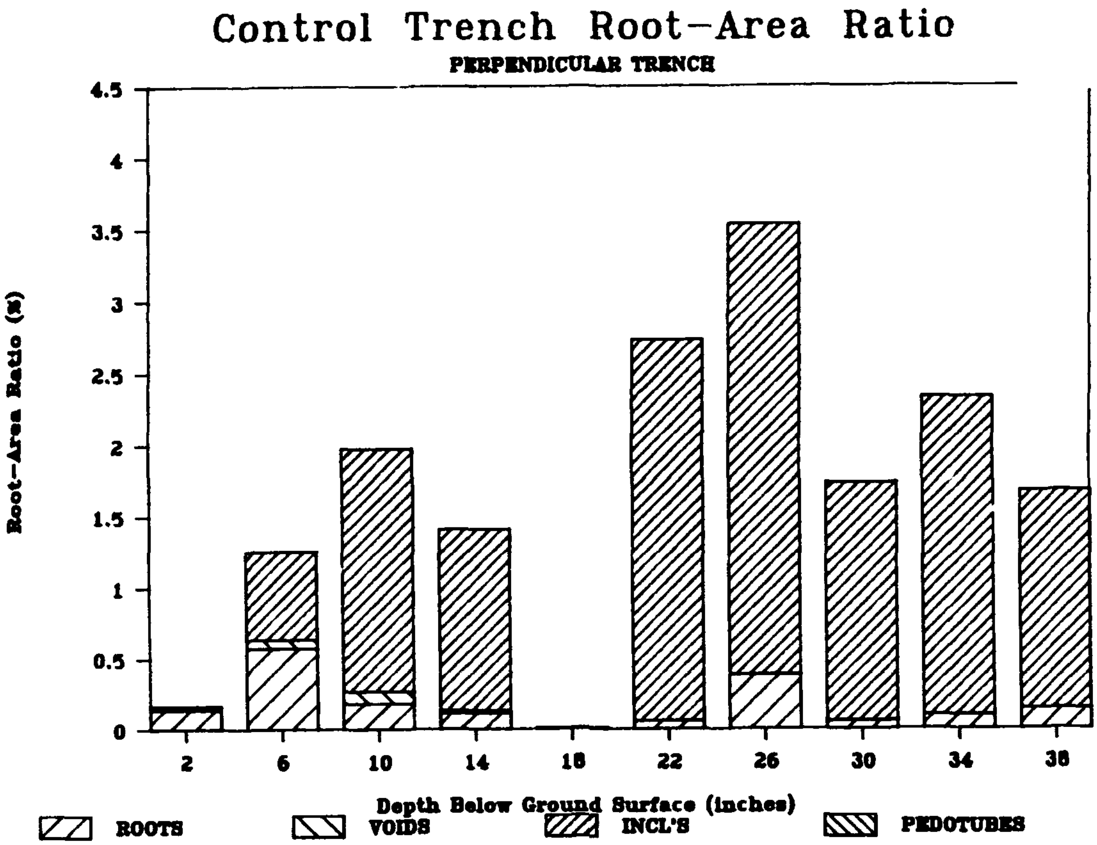
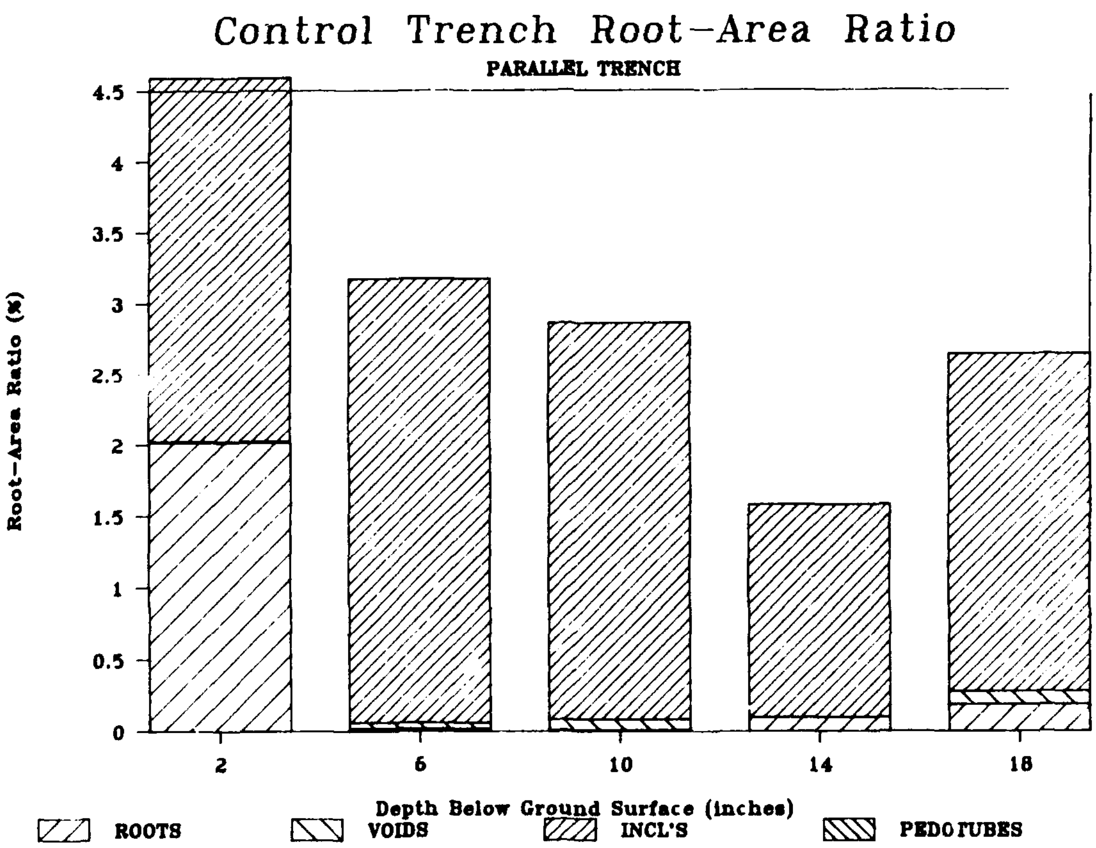
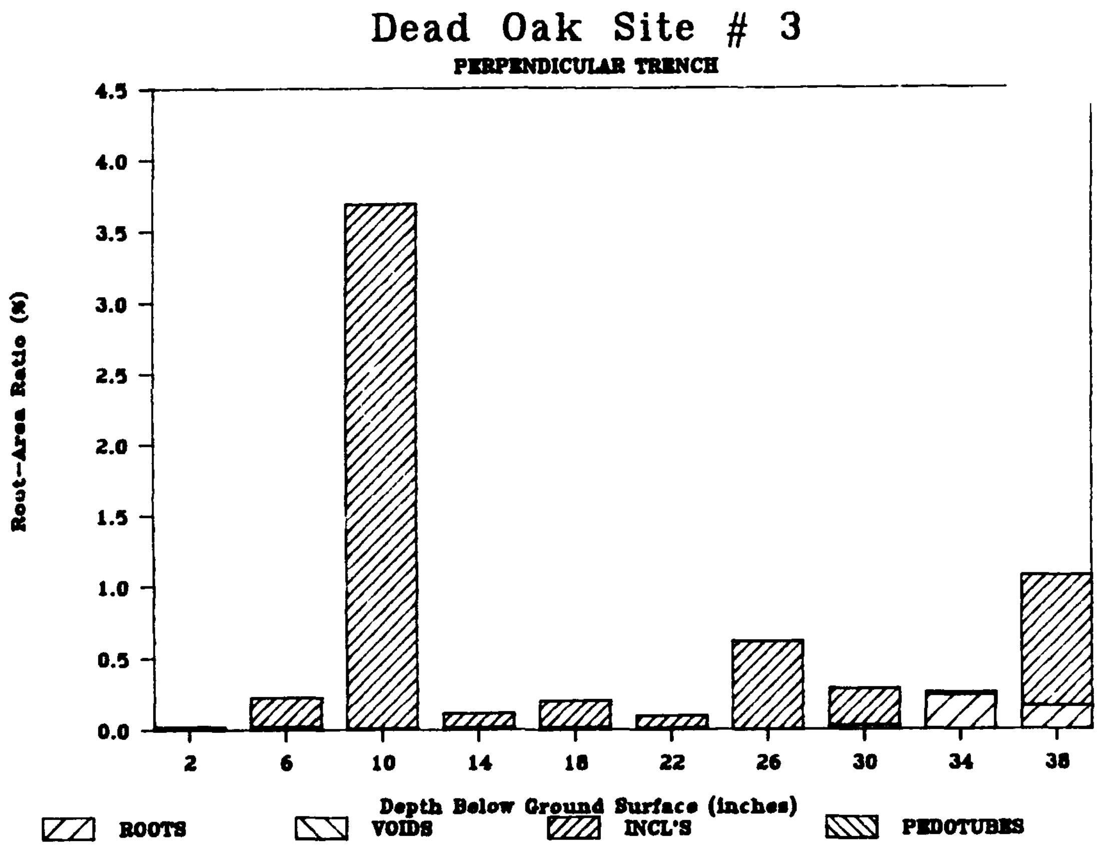
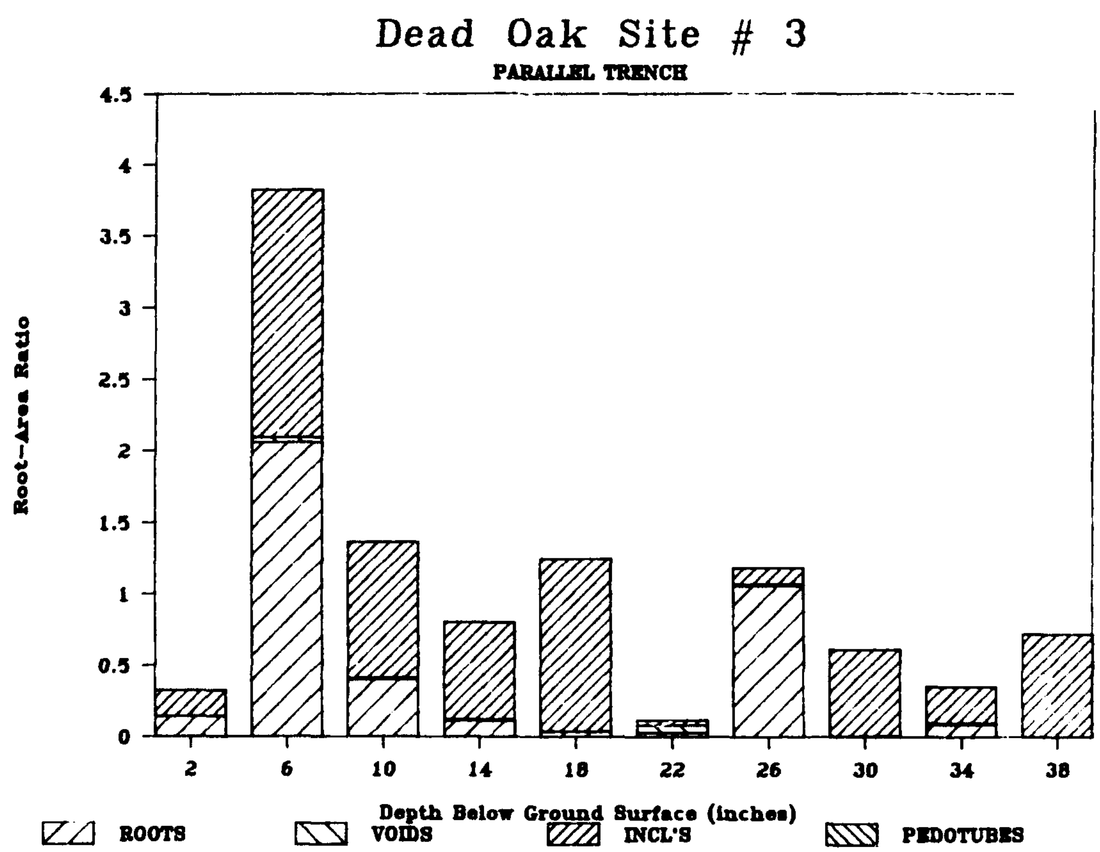
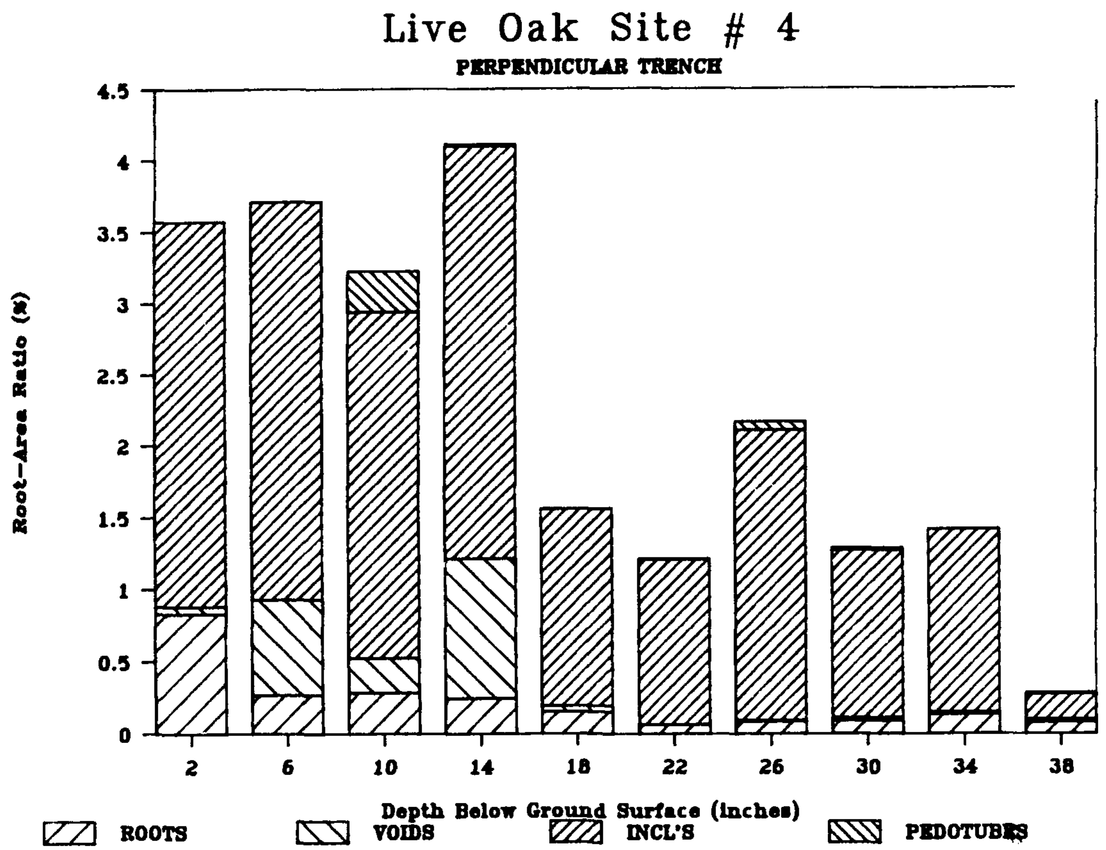
APPENDIX A: TOTAL AREA RATIO HISTOGRAMS FOR LEVEE TRENCH SITES

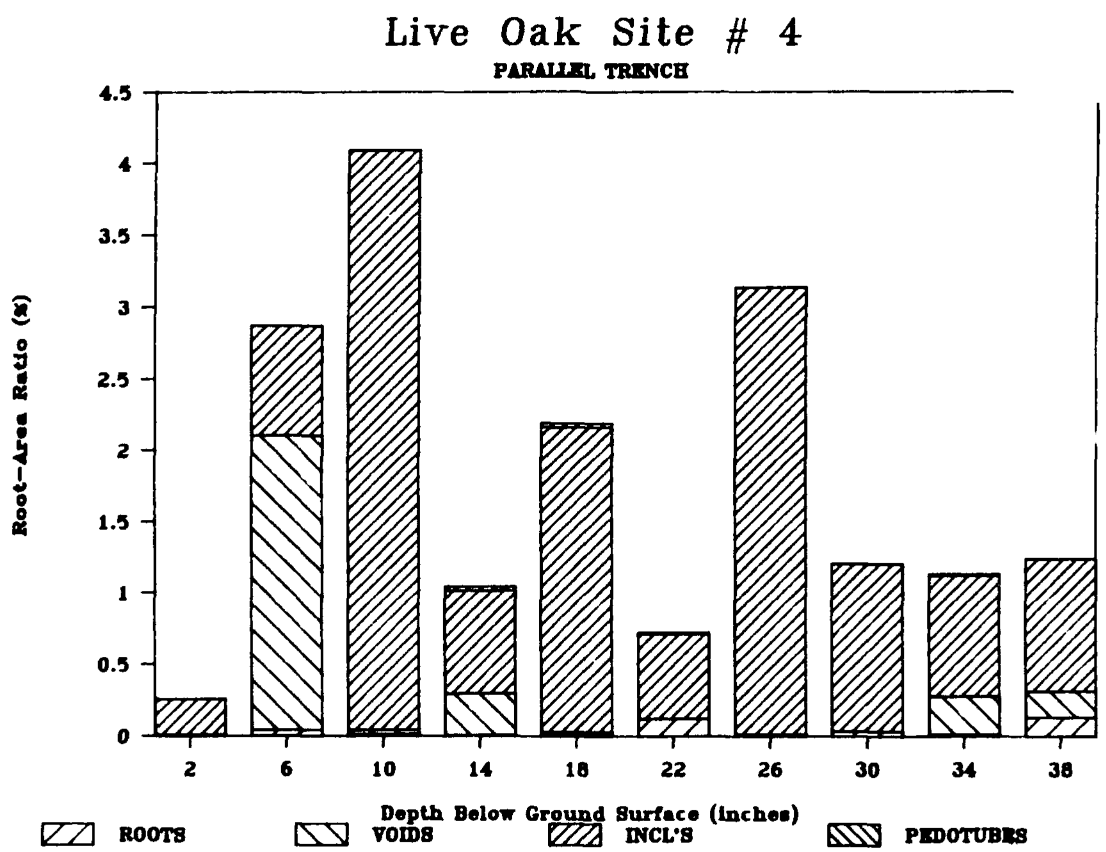

Control Trench Root-Area Ratio
PERPENDICULAR TRENCH
Root-Area Ratio (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

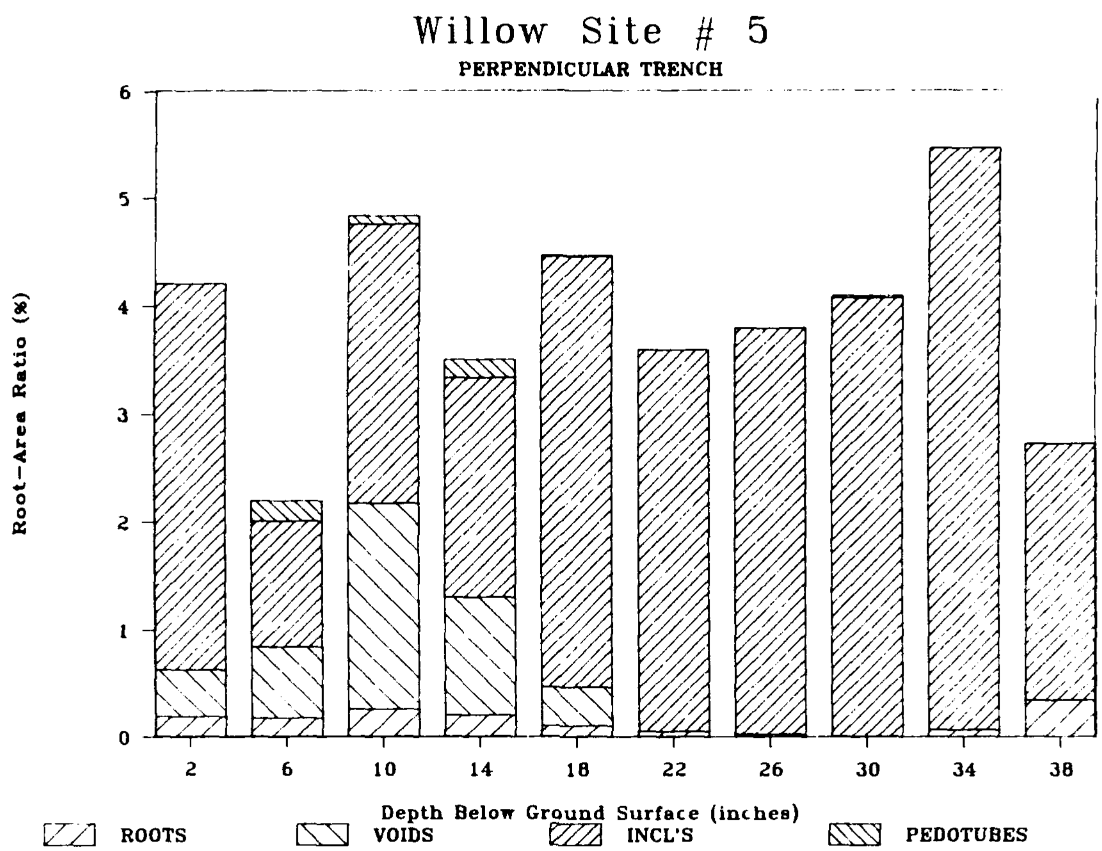

Control Trench Root-Area Ratio
PARALLEL TRENCH
Root-Area Ratio (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
6
10
14
18
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES


Dead Oak Site # 3
PERPENDICULAR TRENCH
Root-Area Ratio (%)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

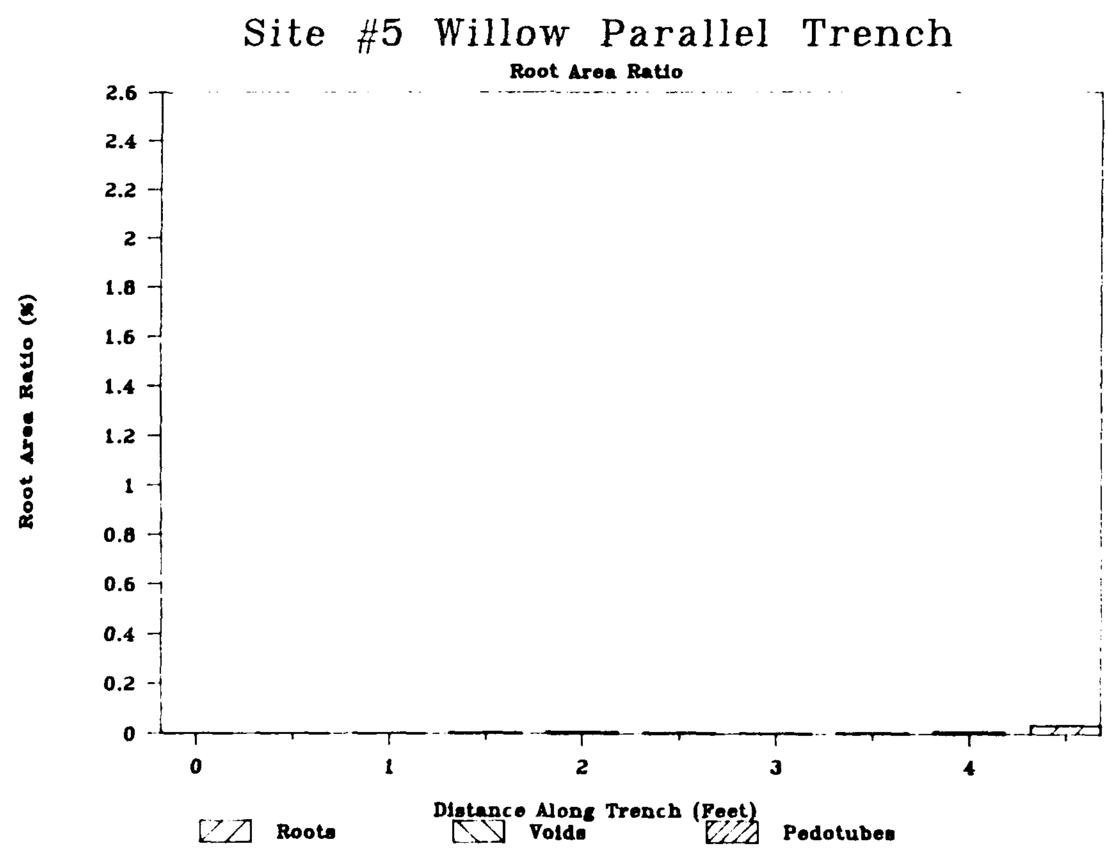

Dead Oak Site # 3
PARALLEL TRENCH
Root-Area Ratio
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES


Live Oak Site # 4
PERPENDICULAR TRENCH
Root-Area Ratio (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

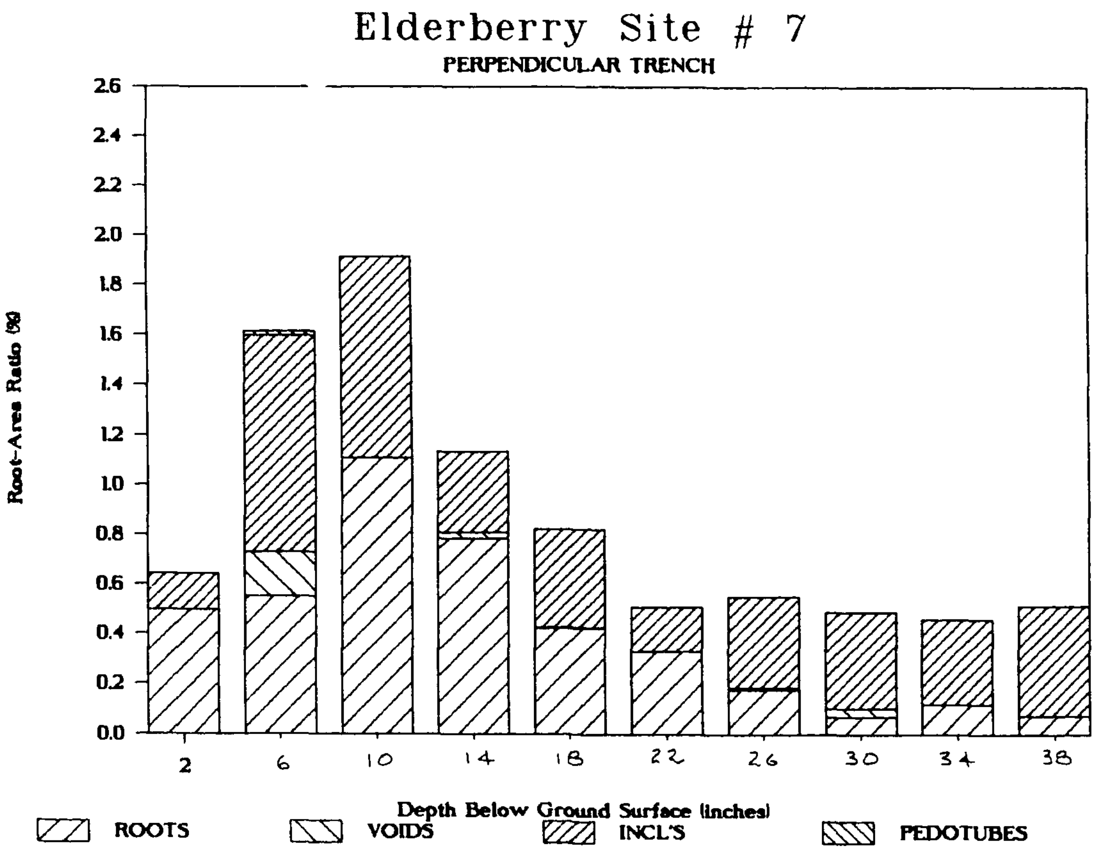

Live Oak Site # 4
PARALLEL TRENCH
Root-Area Ratio (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

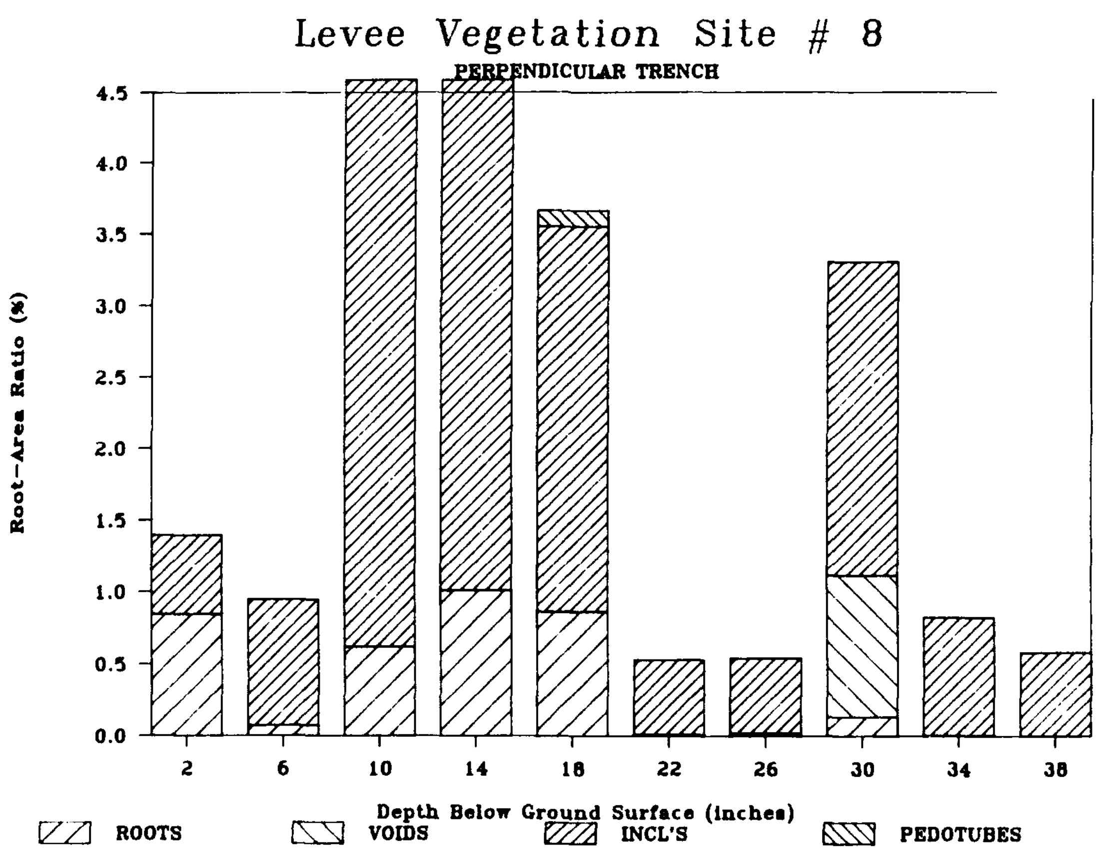


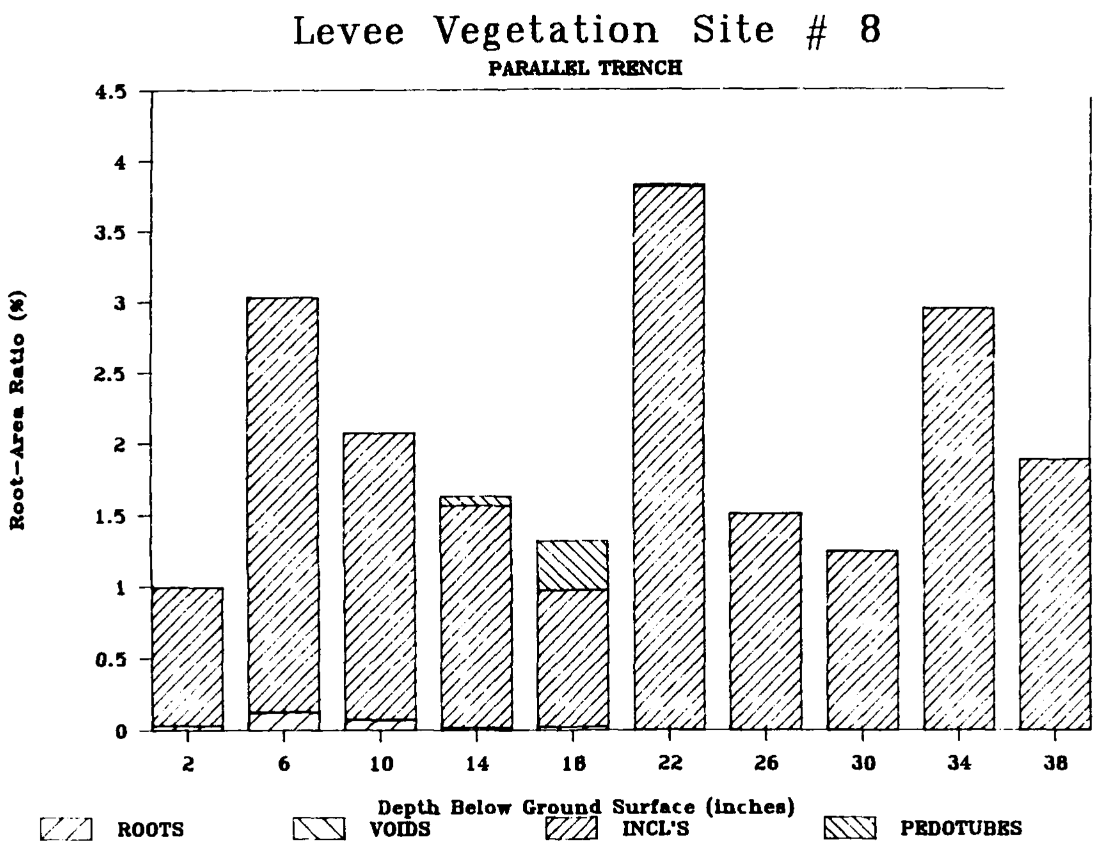
Willow Site # 5
PERPENDICULAR TRENCH
Root-Area Ratio (%)
0
1
2
3
4
5
6
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES



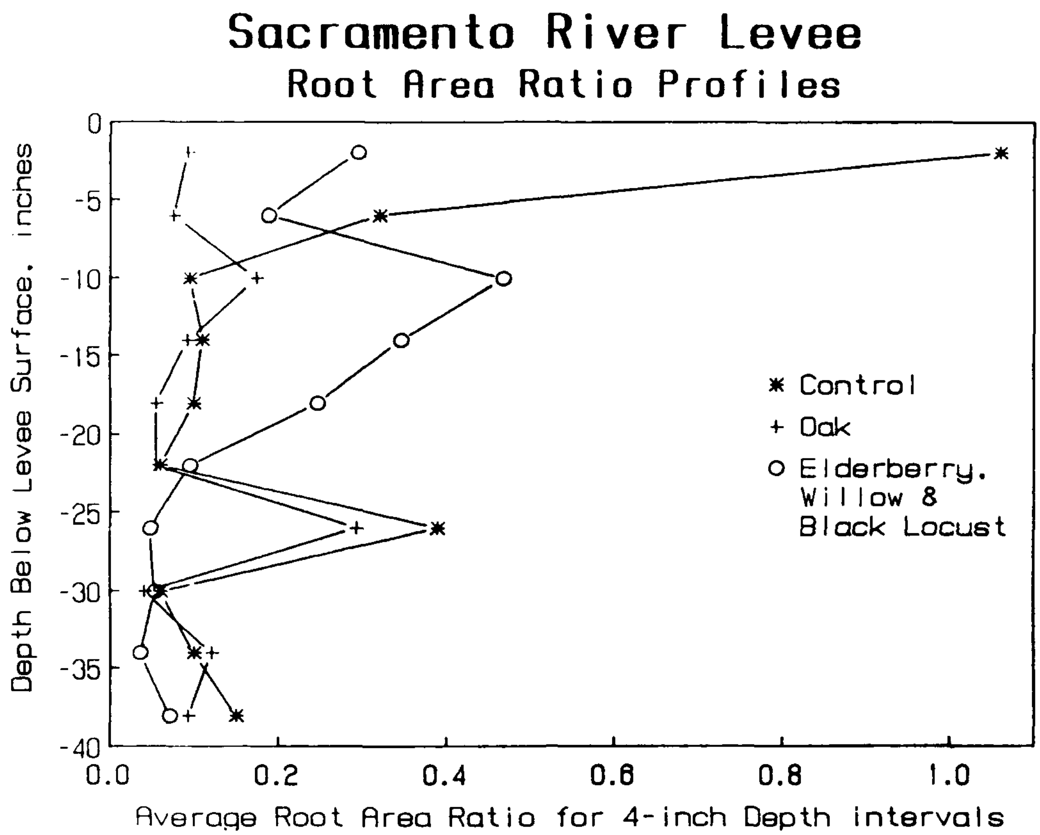
Site #5 Willow Parallel Trench
Root Area Ratio
Root Area Ratio (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
0
1
2
3
4
Distance Along Trench (Feet)
Roots
Voids
Pedotubes

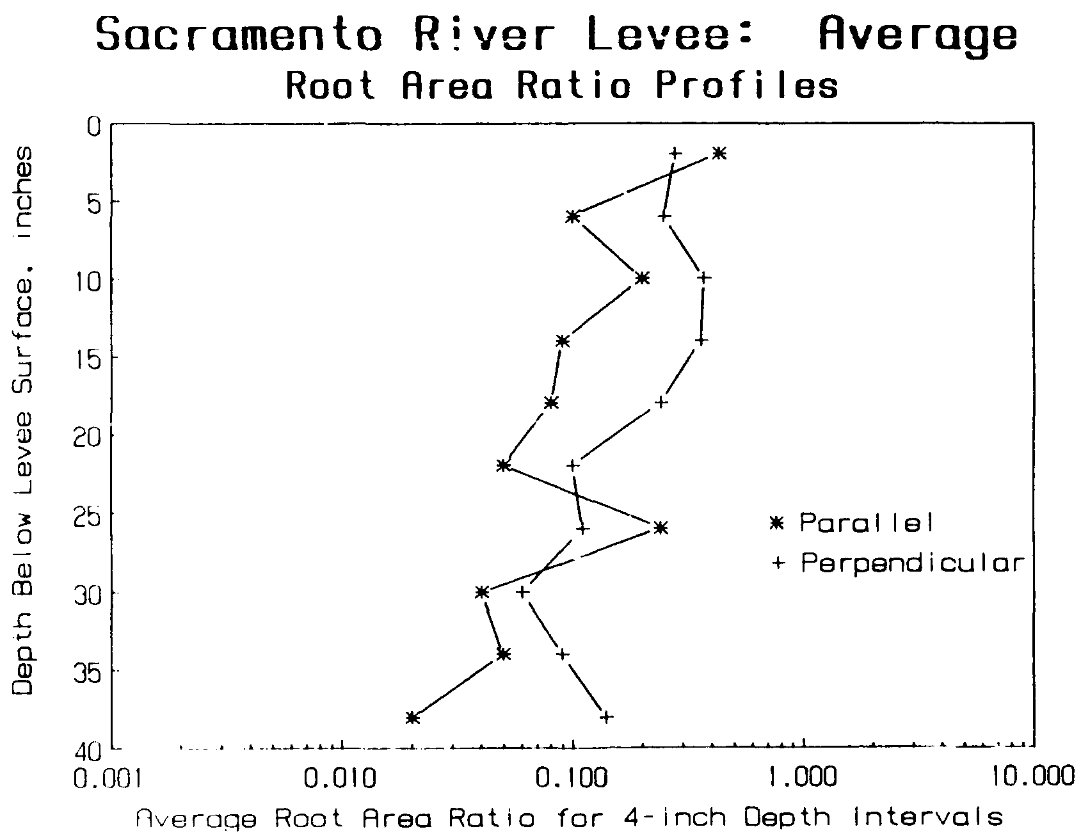

Elderberry Site # 7
PERPENDICULAR TRENCH
Root-Area Ratio (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

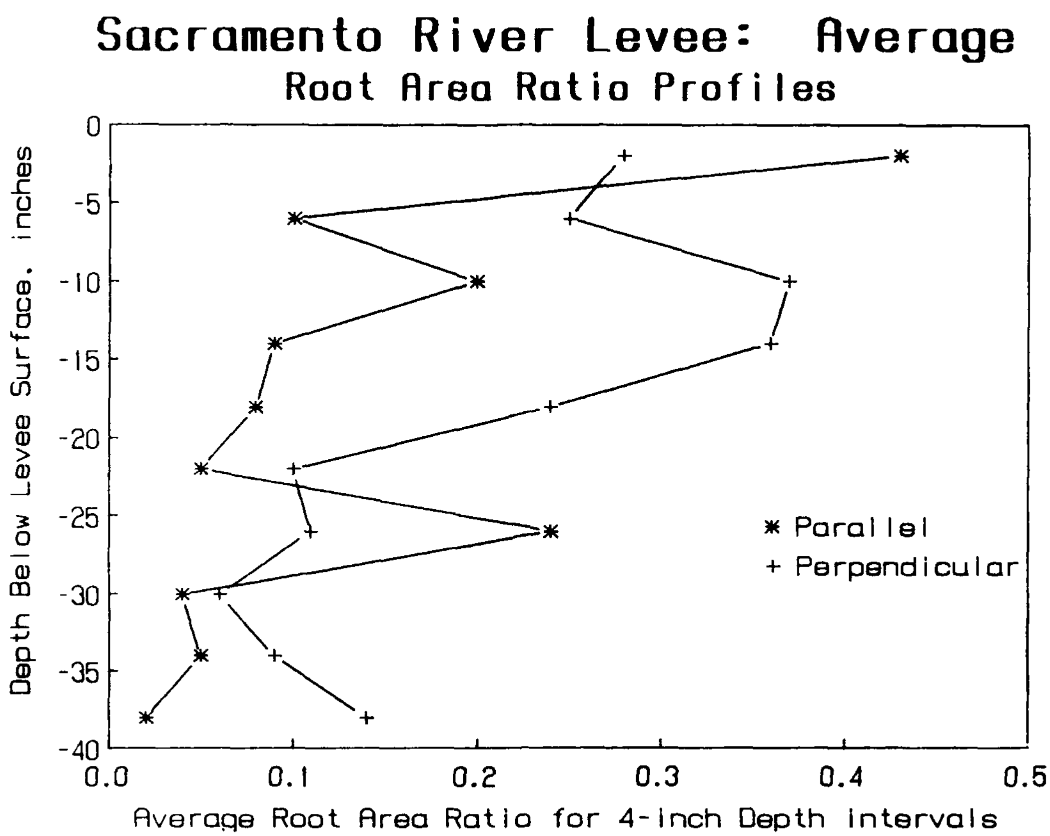

Levee Vegetation Site # 8
PERPENDICULAR TRENCH
Root-Area Ratio (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

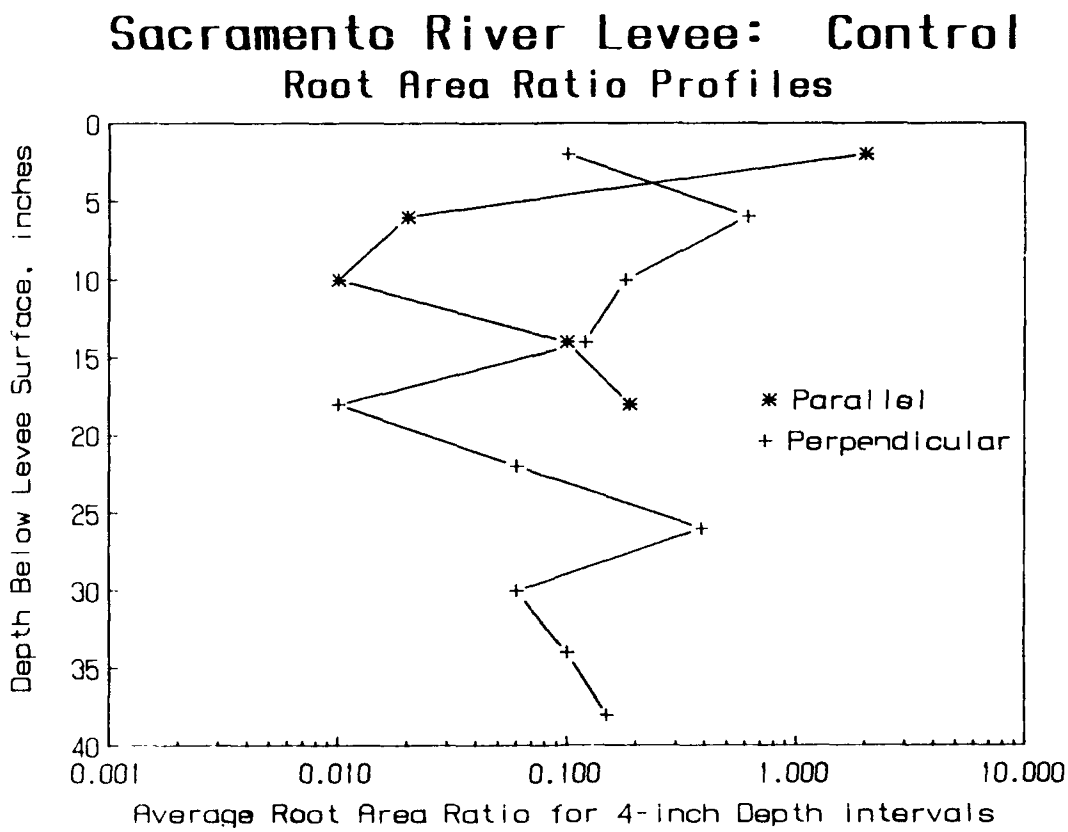

Levee Vegetation Site # 8
PARALLEL TRENCH
Root-Area Ratio (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
6
10
14
18
22
26
30
34
38
Depth Below Ground Surface (inches)
ROOTS
VOIDS
INCL'S
PEDOTUBES

APPENDIX B: ROOT AREA RATIO PROFILES FOR LEVEE TRENCH SITES

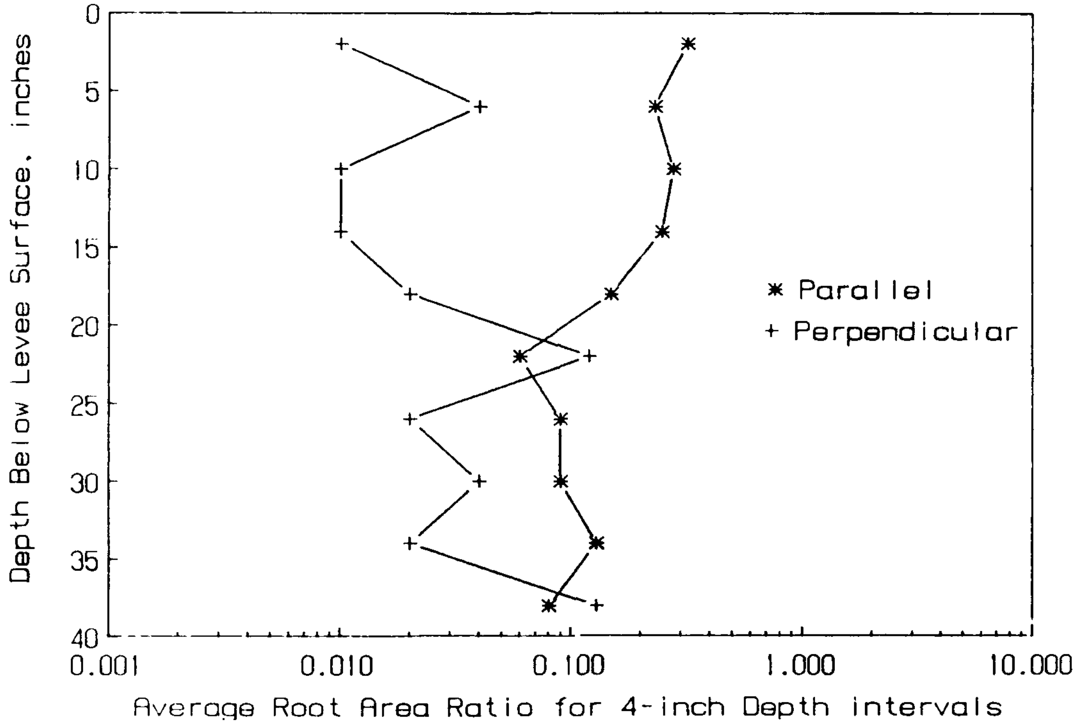

Sacramento River Levee
Root Area Ratio Profiles
Depth Below Levee Surface, inches
0
-5
-10
-15
-20
-25
-30
-35
-40
0.0
0.2
0.4
0.6
0.8
1.0
Average Root Area Ratio for 4-inch Depth intervals
* Control
+ Oak
o Elderberry, Willow & Black Locust


Sacramento River Levee: Average
Root Area Ratio Profiles
Depth Below Levee Surface, inches
0
5
10
15
20
25
30
35
40
0.001
0.010
0.100
1.000
10.000
Average Root Area Ratio for 4-inch Depth Intervals
* Parallel
+ Perpendicular

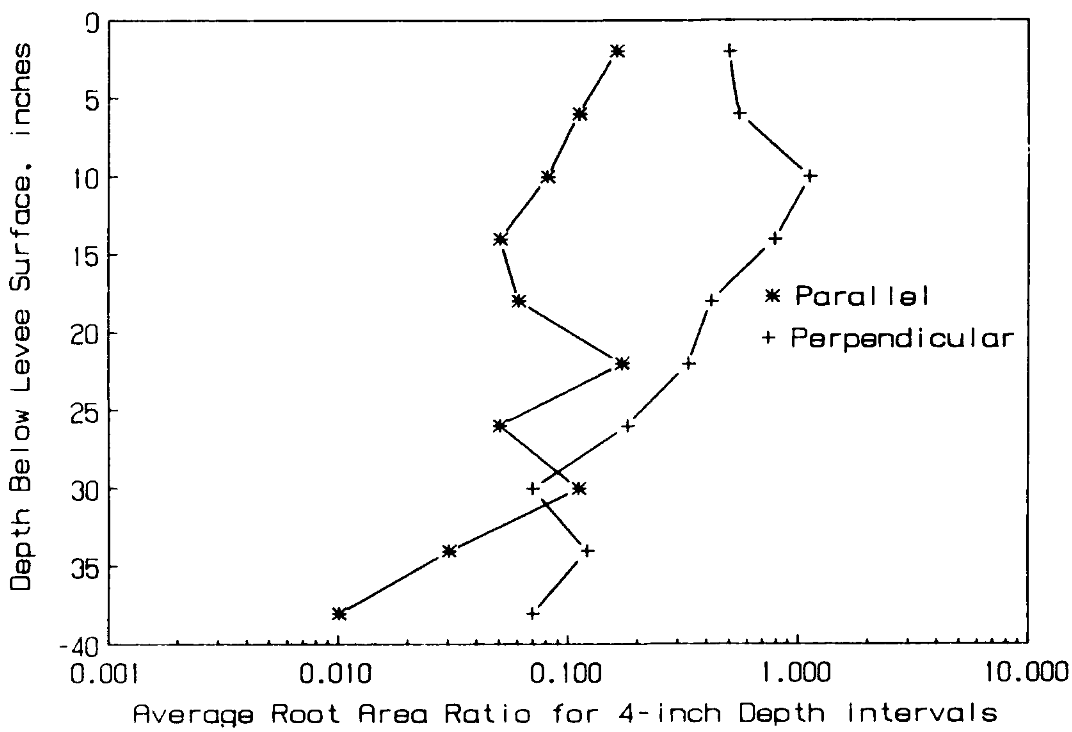

Sacramento River Levee: Average
Root Area Ratio Profiles
Depth Below Levee Surface, inches
Average Root Area Ratio for 4-inch Depth intervals
0
-5
-10
-15
-20
-25
-30
-35
-40
0.0
0.1
0.2
0.3
0.4
0.5
✱ Parallel
+ Perpendicular

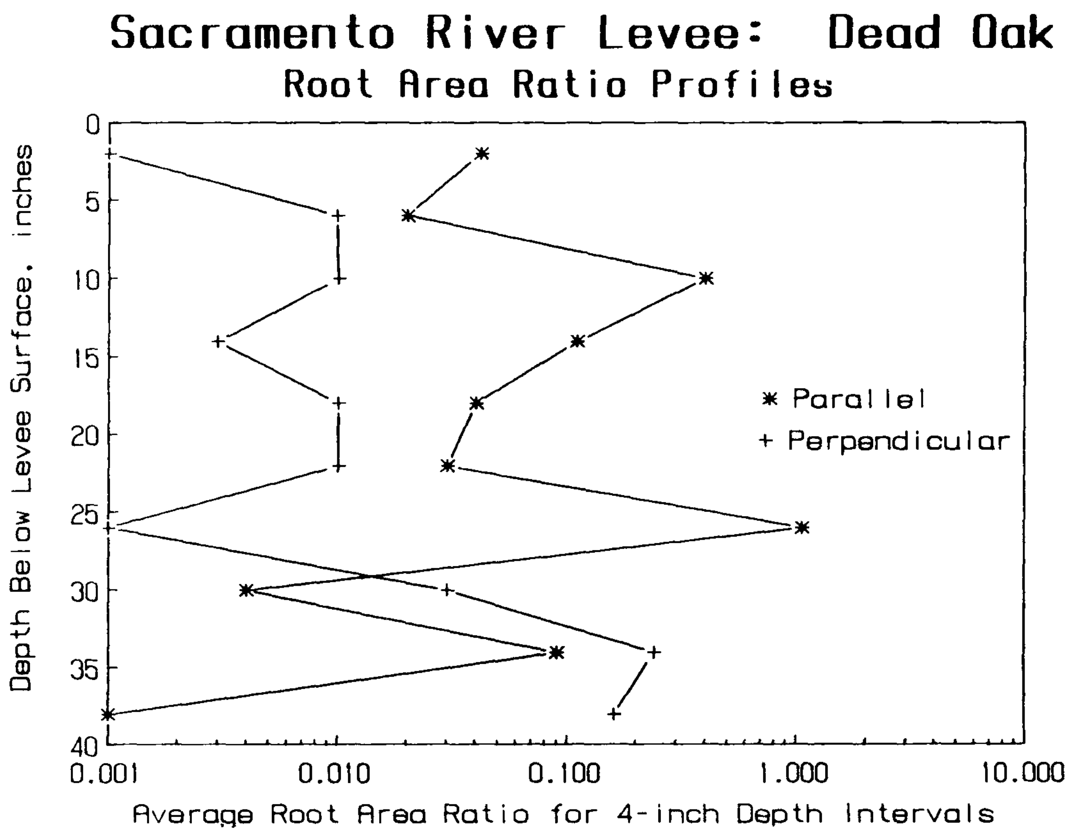

Sacramento River Levee: Control
Root Area Ratio Profiles
Depth Below Levee Surface, inches
Average Root Area Ratio for 4-inch Depth intervals
0
5
10
15
20
25
30
35
40
0.001
0.010
0.100
1.000
10.000
✱ Parallel
+ Perpendicular

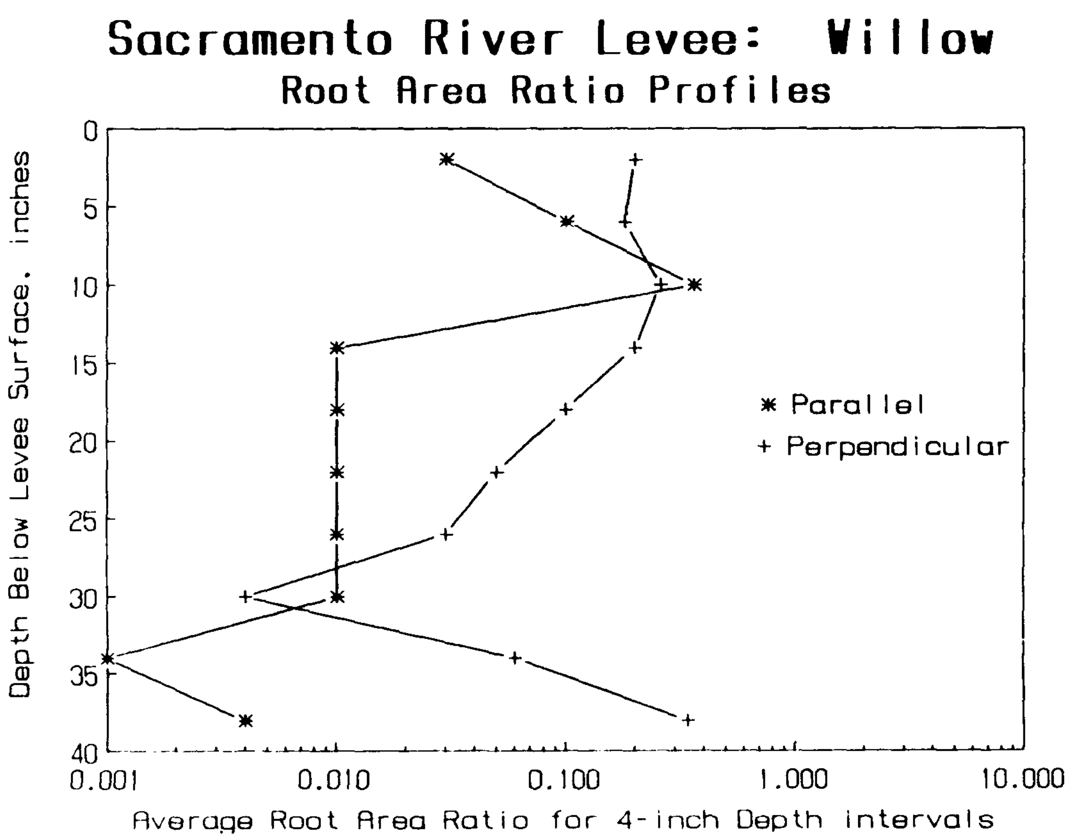
Sacramento River Levee: Live Oak
Root Area Ratio Profiles

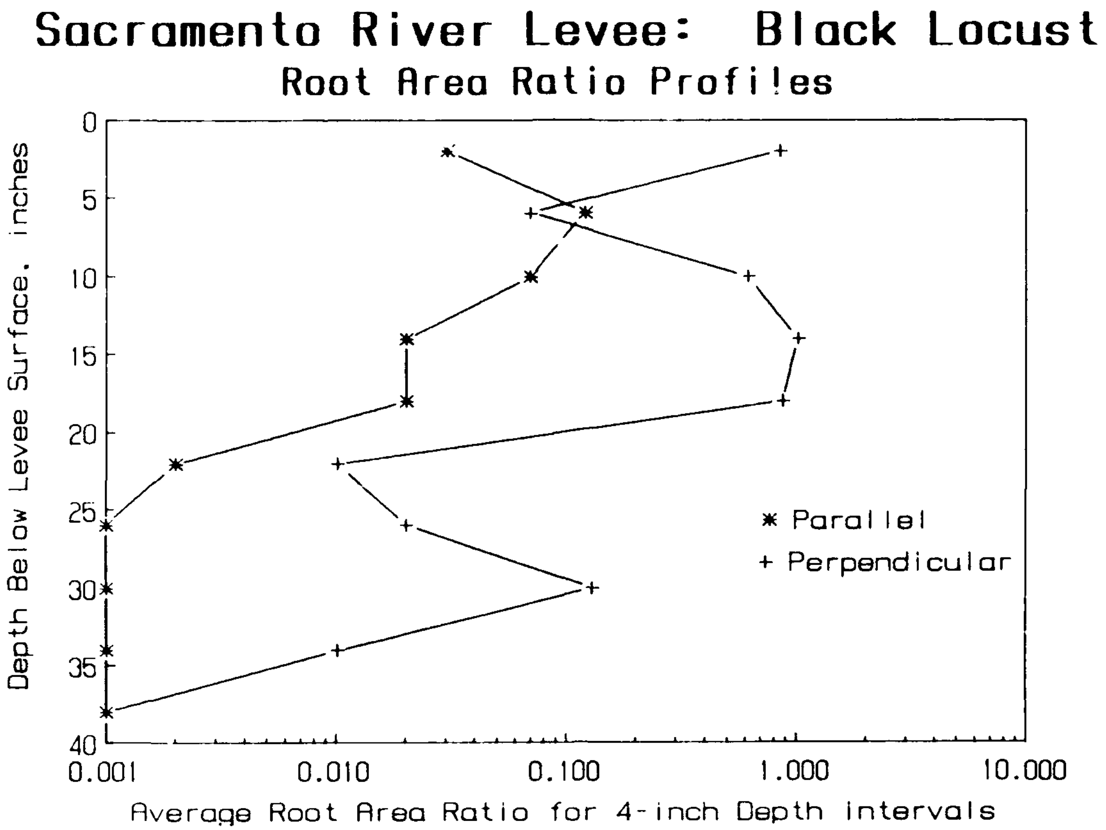


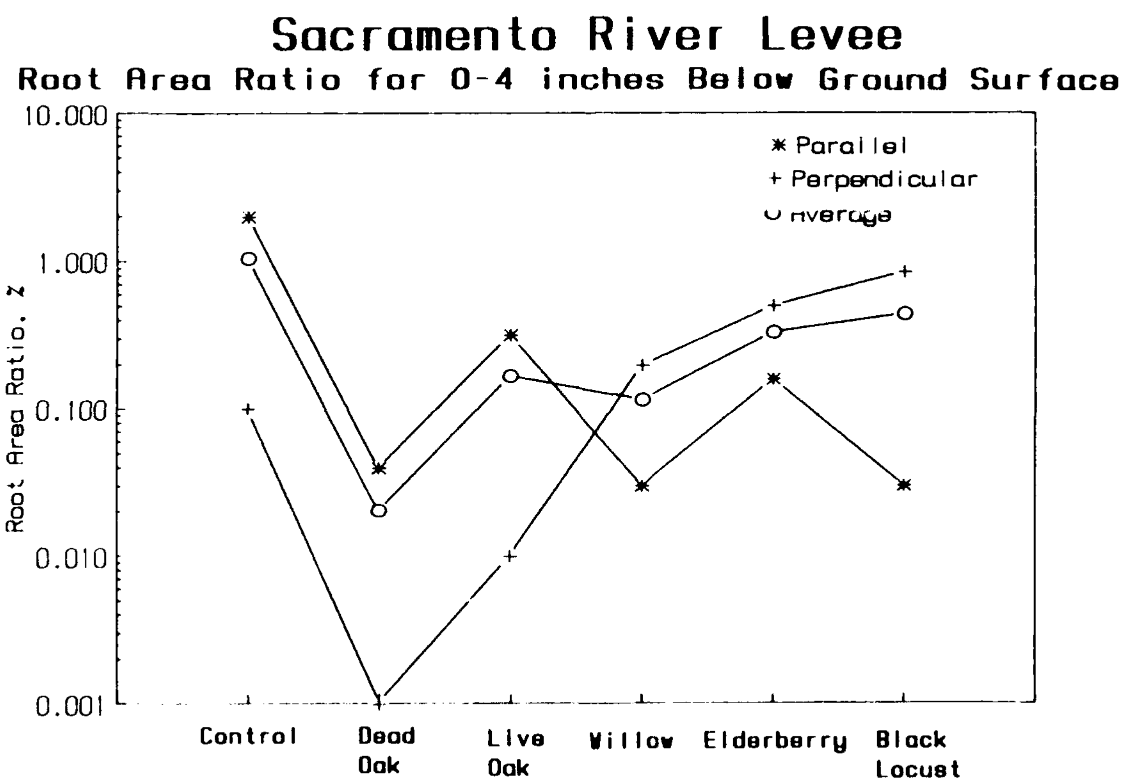
Sacramento River Levee: Elderberry
Root Area Ratio Profiles

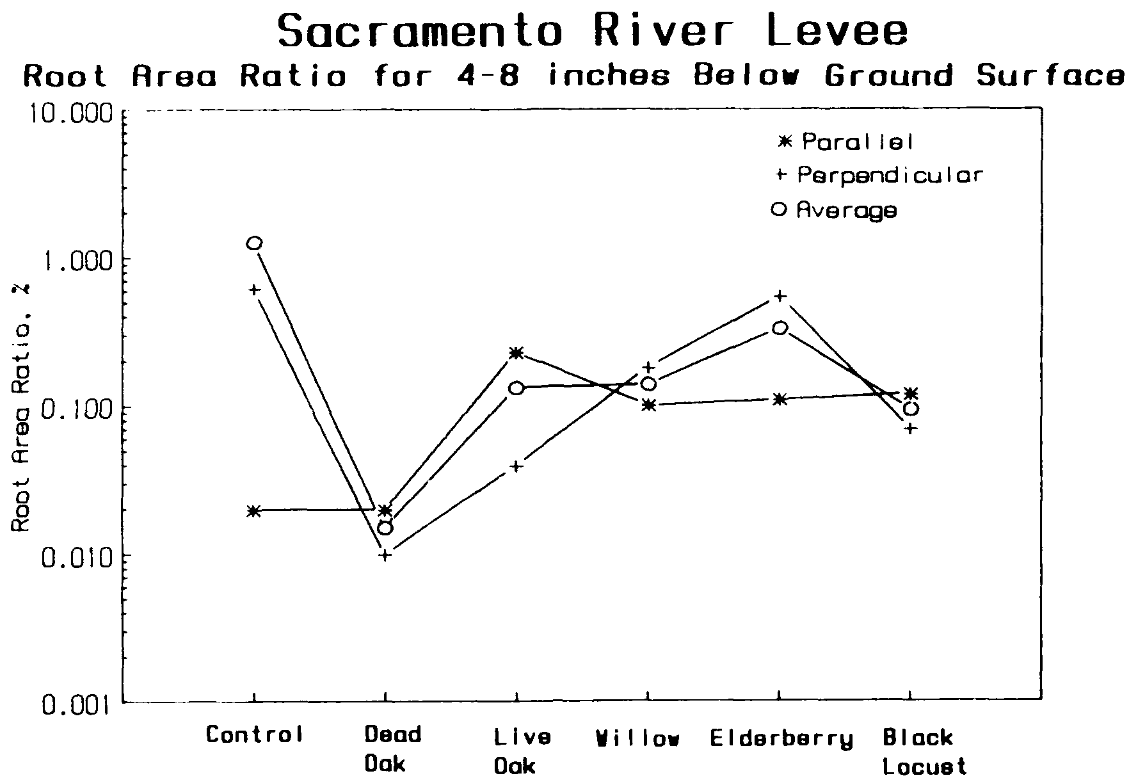



Sacramento River Levee: Dead Oak
Root Area Ratio Profiles
Depth Below Levee Surface, inches
0
5
10
15
20
25
30
35
40
0.001
0.010
0.100
1.000
10.000
Average Root Area Ratio for 4-inch Depth Intervals
* Parallel
+ Perpendicular

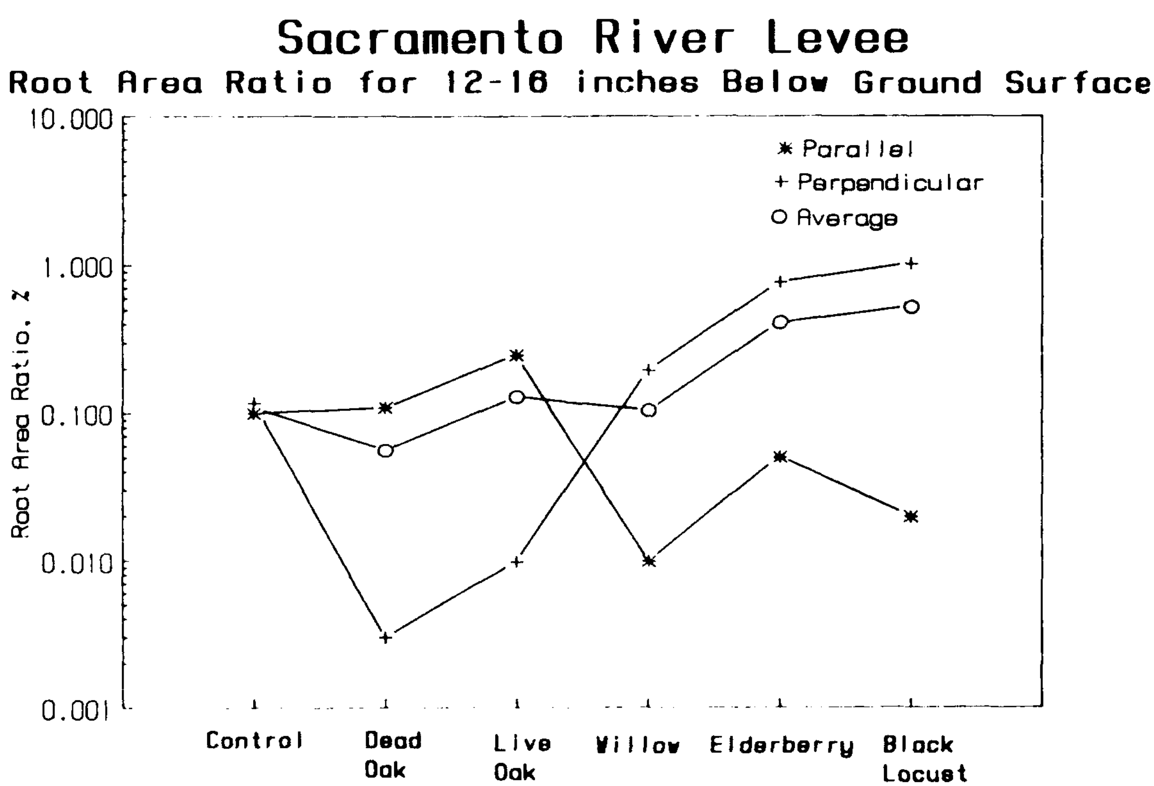

Sacramento River Levee: Willow
Root Area Ratio Profiles
Depth Below Levee Surface, inches
0
5
10
15
20
25
30
35
40
0.001
0.010
0.100
1.000
10.000
Average Root Area Ratio for 4-inch Depth intervals
* Parallel
+ Perpendicular


Sacramento River Levee: Black Locust
Root Area Ratio Profiles
Depth Below Levee Surface, inches
0
5
10
15
20
25
30
35
40
0.001
0.010
0.100
1.000
10.000
Average Root Area Ratio for 4-inch Depth intervals
✱ Parallel
+ Perpendicular

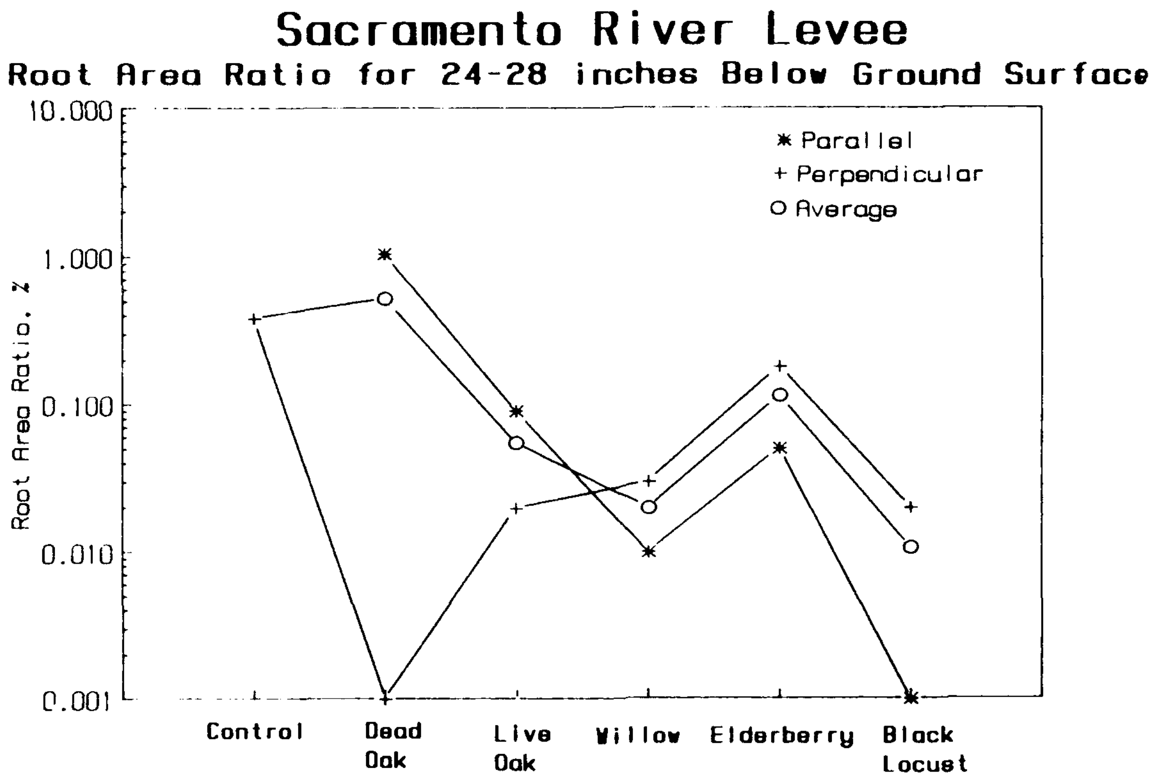

Sacramento River Levee
Root Area Ratio for 0-4 inches Below Ground Surface
Root Area Ratio, %
10.000
1.000
0.100
0.010
0.001
✱ Parallel
+ Perpendicular
○ Average
Control
Dead Oak
Live Oak
Willow
Elderberry
Black Locust



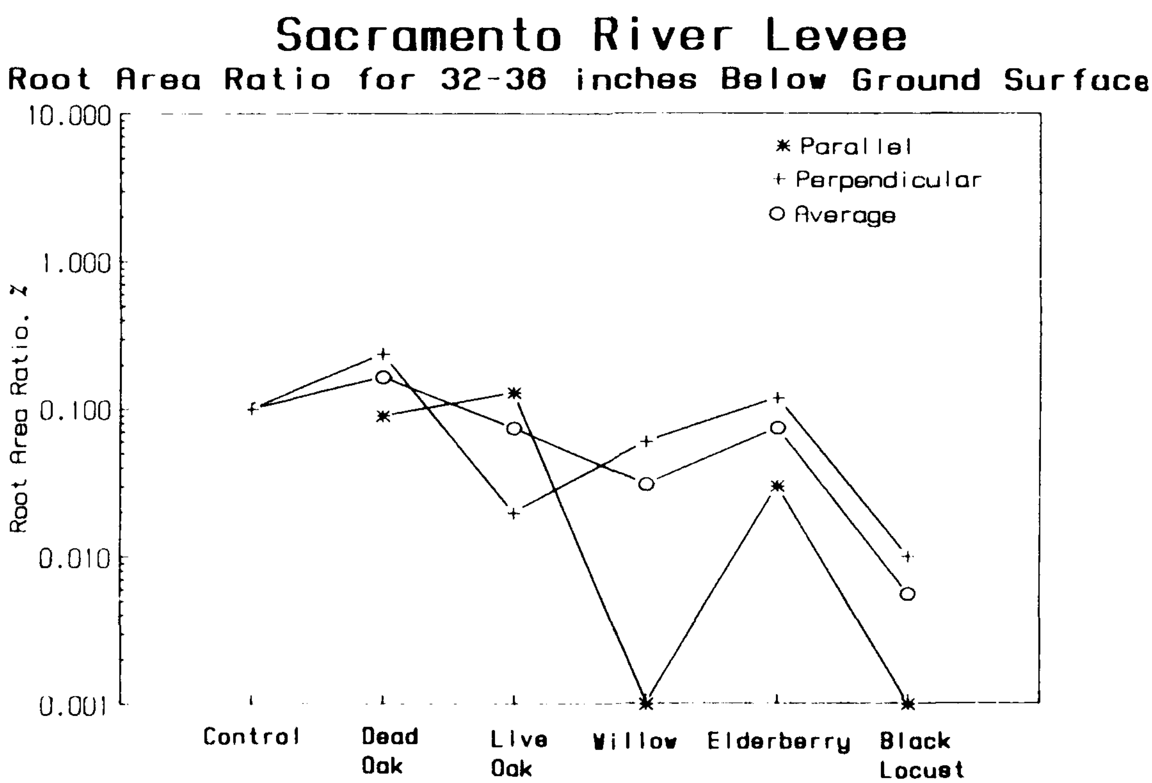
Sacramento River Levee
Root Area Ratio for 4-8 inches Below Ground Surface
10.000
1.000
0.100
0.010
0.001
Root Area Ratio, %
* Parallel
+ Perpendicular
O Average
Control
Dead Oak
Live Oak
Willow
Elderberry
Black Locust



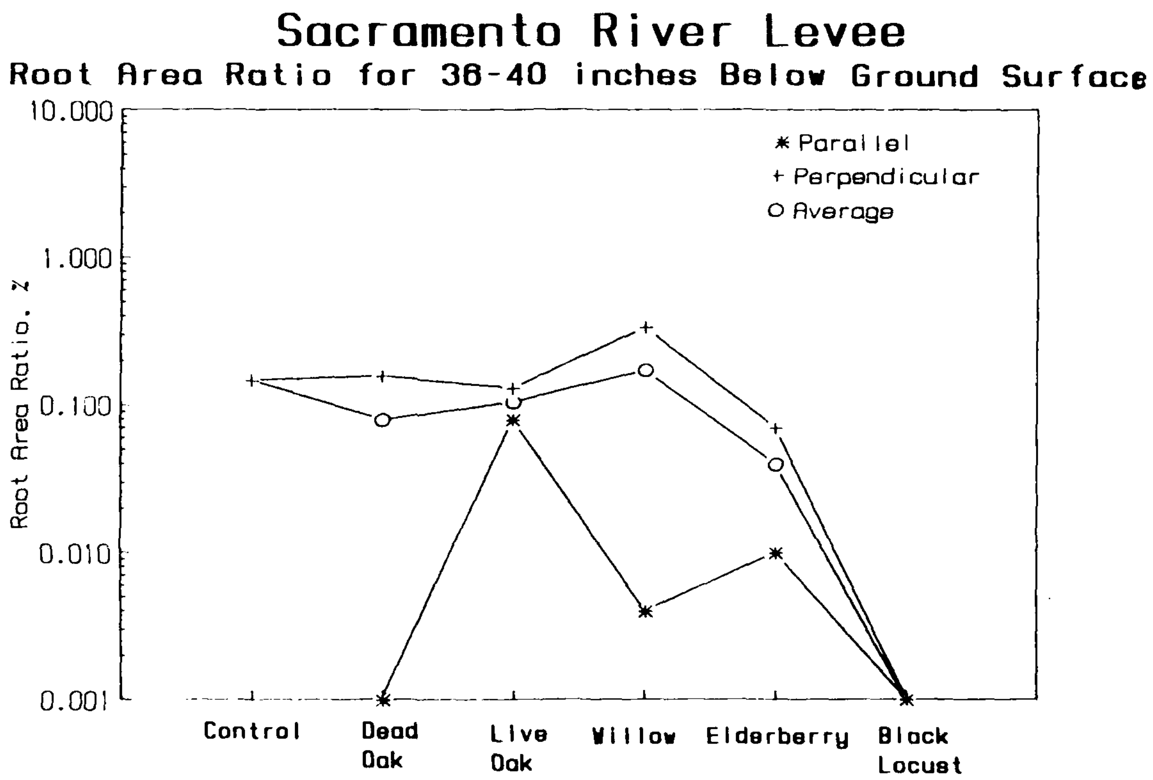
Sacramento River Levee
Root Area Ratio for 12-16 inches Below Ground Surface
10.000
1.000
0.100
0.010
0.001
Root Area Ratio, %
* Parallel
+ Perpendicular
O Average
Control
Dead Oak
Live Oak
Willow
Elderberry
Black Locust



Sacramento River Levee
Root Area Ratio for 24-28 inches Below Ground Surface
10.000
1.000
0.100
0.010
0.001
Root Area Ratio, %
* Parallel
+ Perpendicular
O Average
Control
Dead Oak
Live Oak
Willow
Elderberry
Black Locust



Sacramento River Levee
Root Area Ratio for 32-36 inches Below Ground Surface
10.000
1.000
0.100
0.010
0.001
Root Area Ratio, %
* Parallel
+ Perpendicular
O Average
Control
Dead Oak
Live Oak
Willow
Elderberry
Black Locust



Sacramento River Levee
Root Area Ratio for 36-40 inches Below Ground Surface
Root Area Ratio, %
10.000
1.000
0.100
0.010
0.001
* Parallel
+ Perpendicular
O Average
Control
Dead Oak
Live Oak
Willow
Elderberry
Black Locust

APPENDIX C: ROOT SIZE DISTRIBUTION PLOTS FOR LEVEE TRENCH SITES

Explanation of Three-dimensional Plots

X axis--log of number of roots per square foot.

Y axis--root size class.

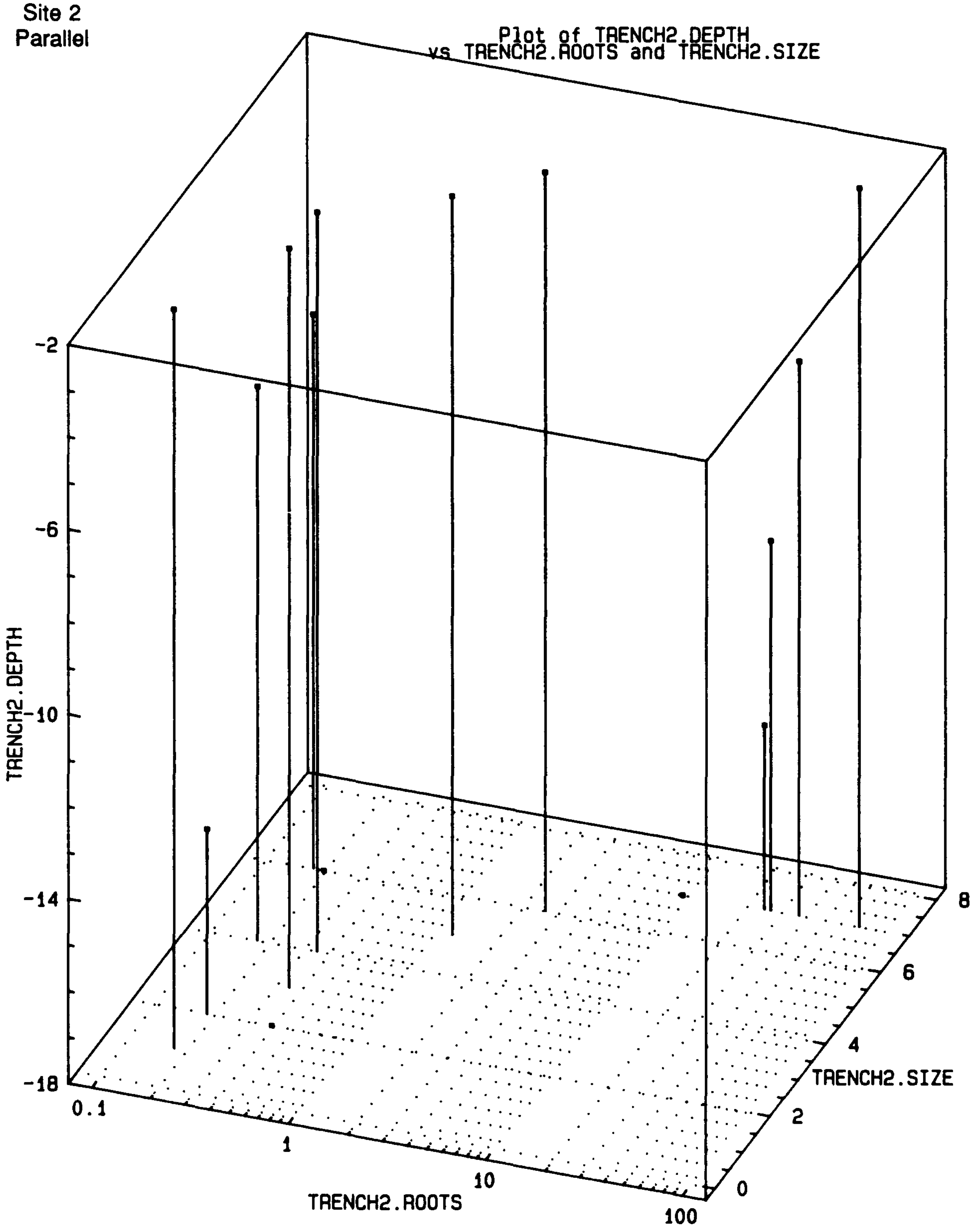
1	> 30 mm
2	20-30 mm
3	10-20 mm
4	5-10 mm
5	2-5 mm
6	1-2 mm
7	< 1 mm

Most of the Y scales range from 0 to 8, but a few have smaller ranges. Scales were set automatically by the plot package.

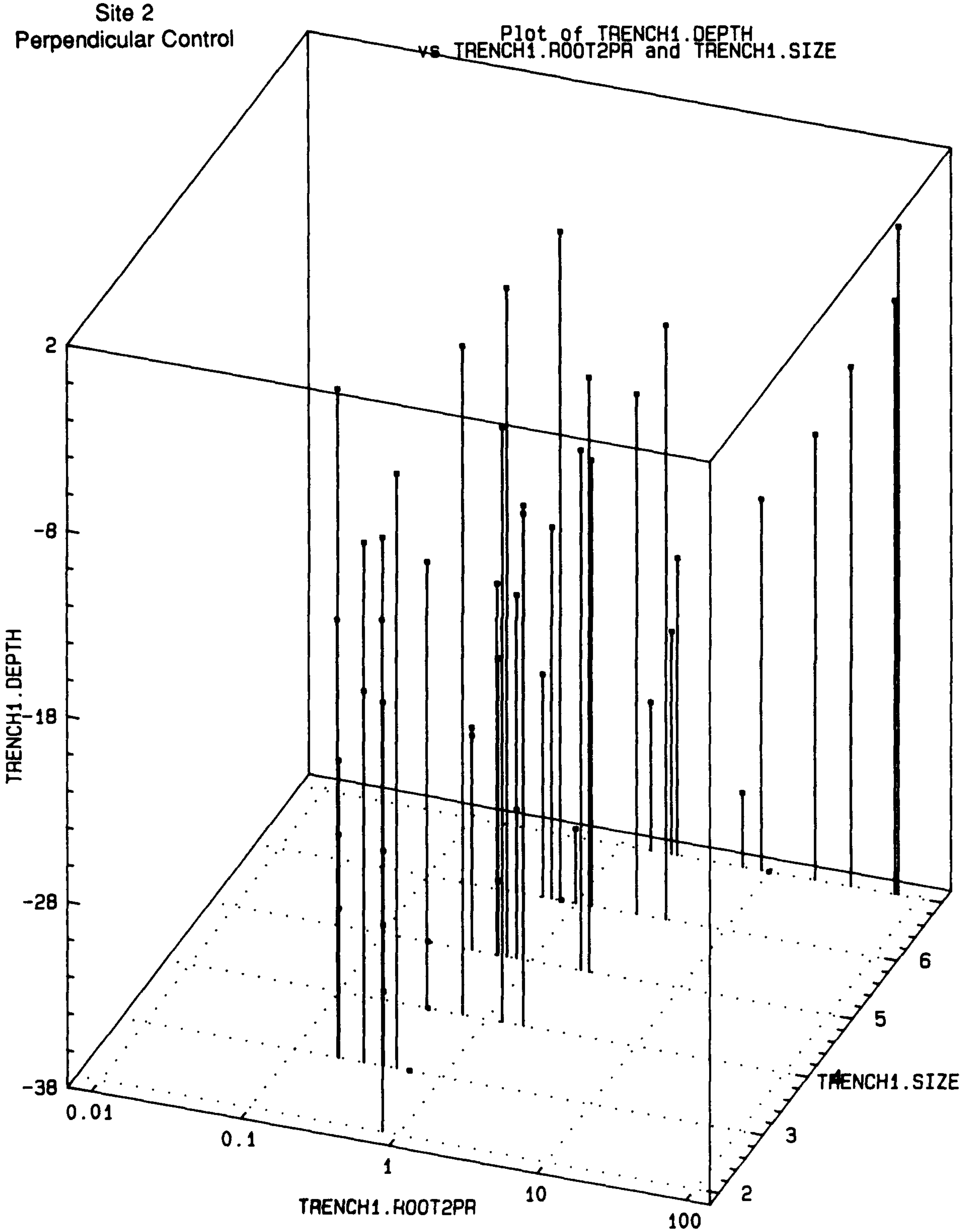
Z (vertical) axis--depth below surface in inches times -1. The upper limit of +2 was set by the automatic scaling routine in the plot software--there has been some trouble with the software when attempts are made to manually set the scales. Note that all plots have Z axes scaled from +2 to -38, except site 2 (parallel) and site 3 (perpendicular).

To use all of the plots in the report, the software could probably be forced to use uniform scales, with a little more effort. The authors are not advocating inclusion of these plots in the report, however. They were produced only to facilitate examination of the data.

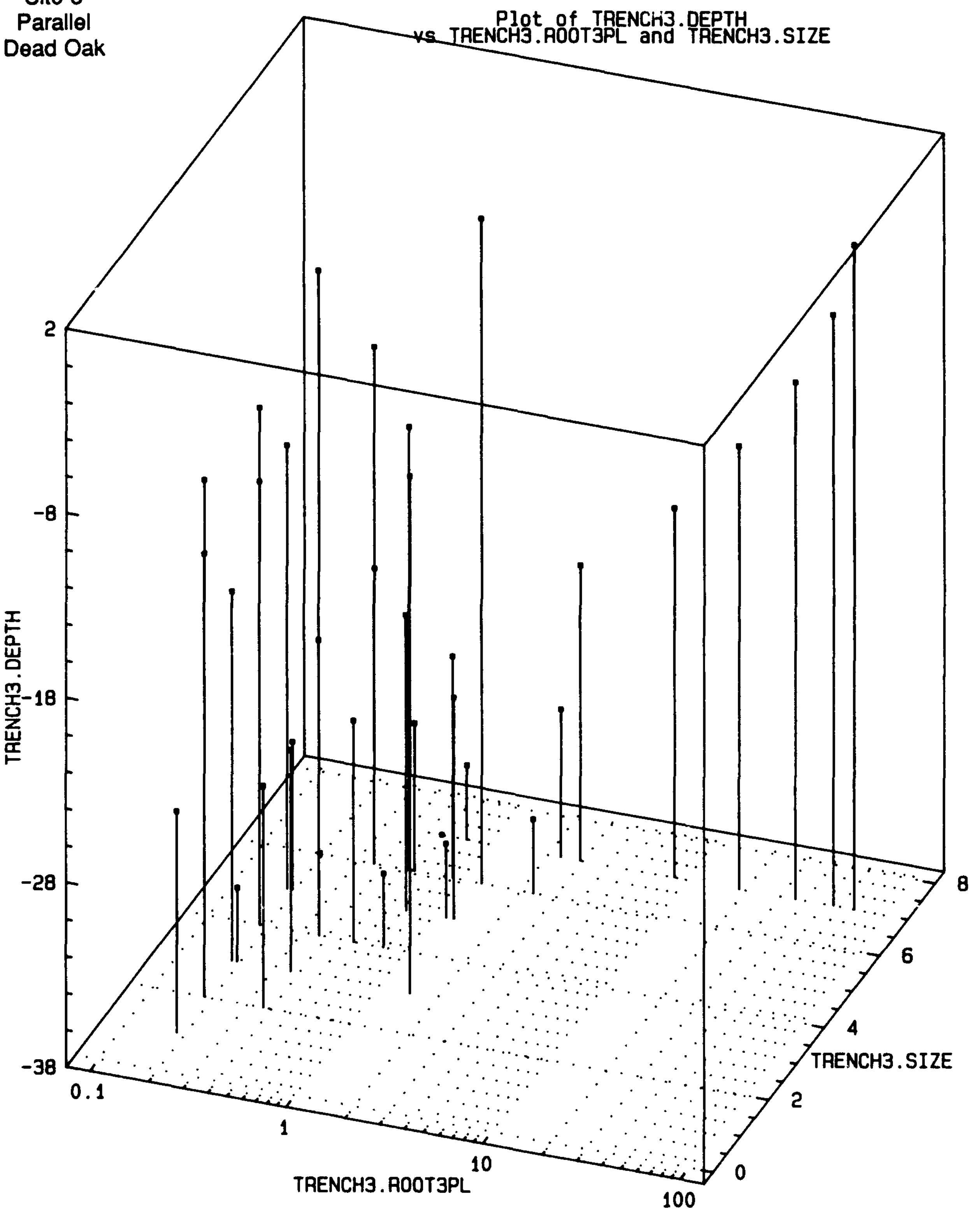
Site 2
Parallel



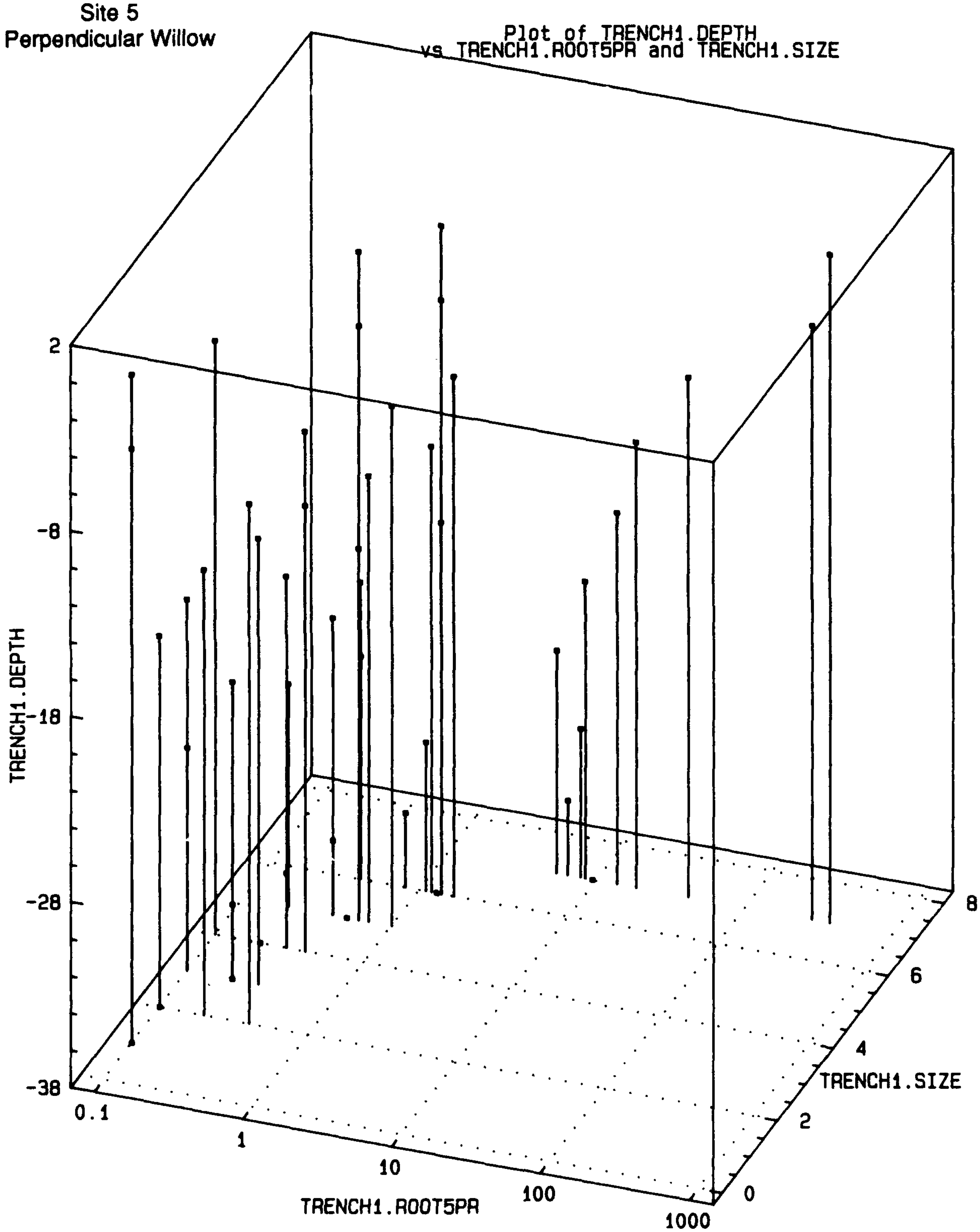
Site 2
Perpendicular Control



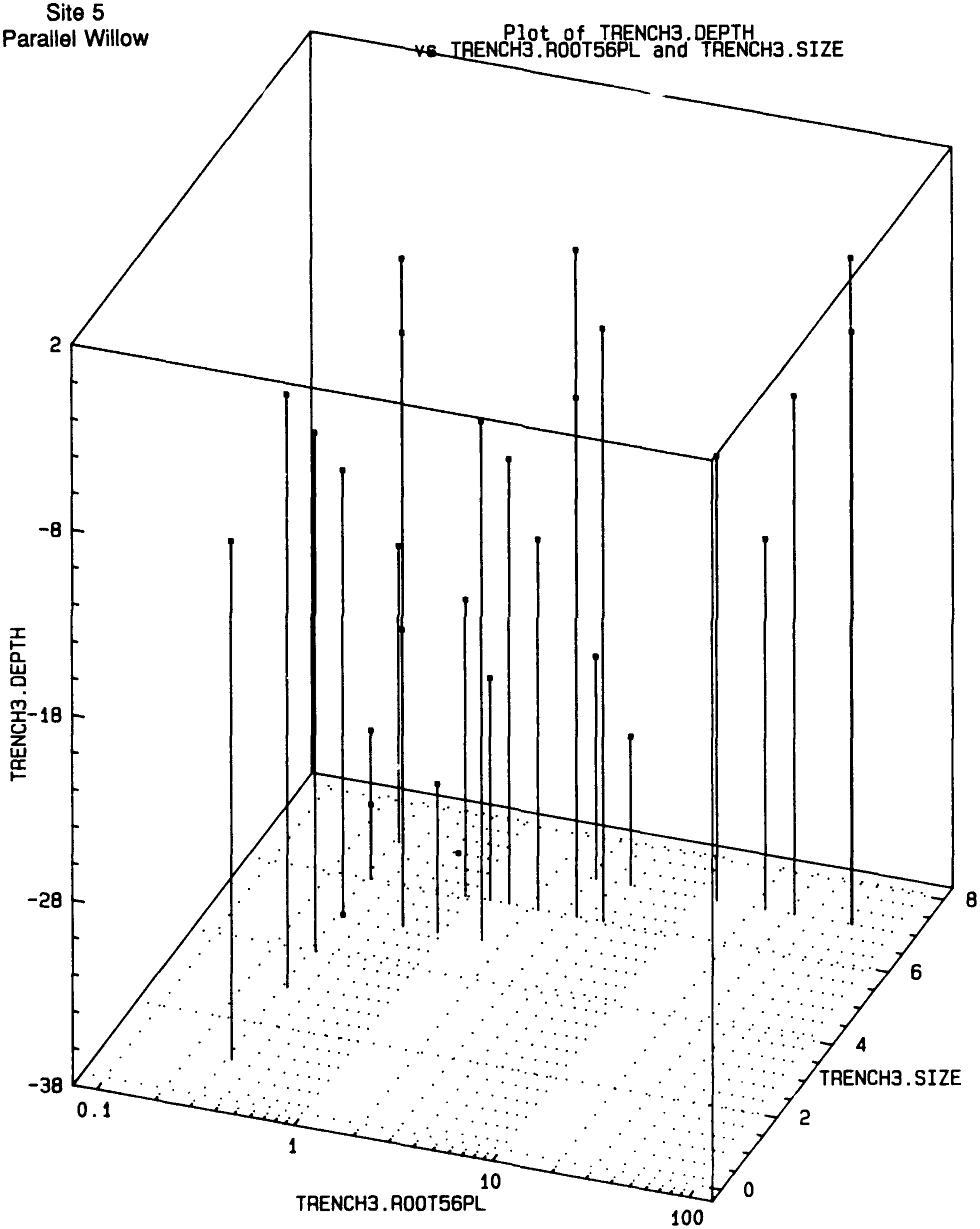
Site 3
Parallel
Dead Oak



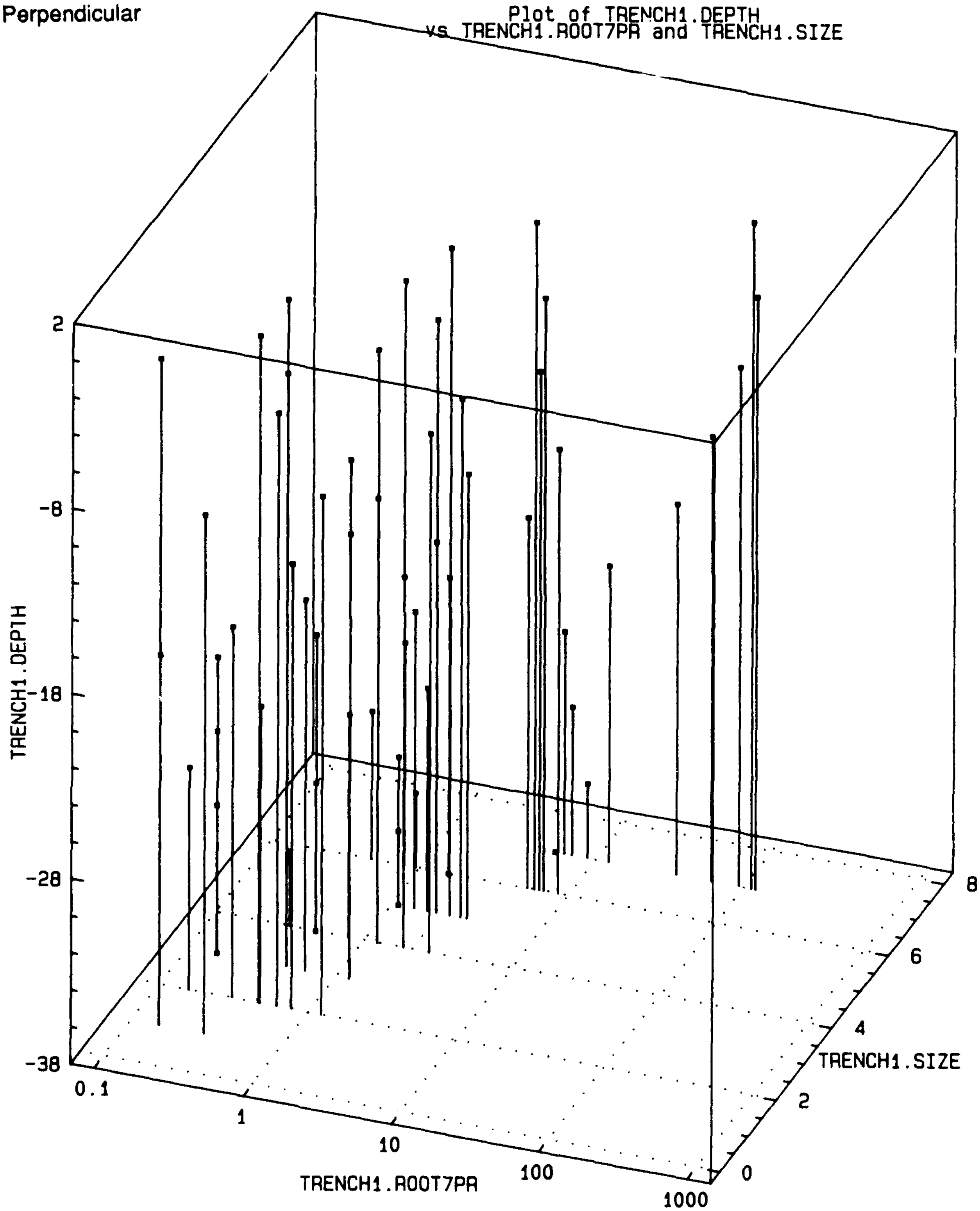
Site 5
Perpendicular Willow



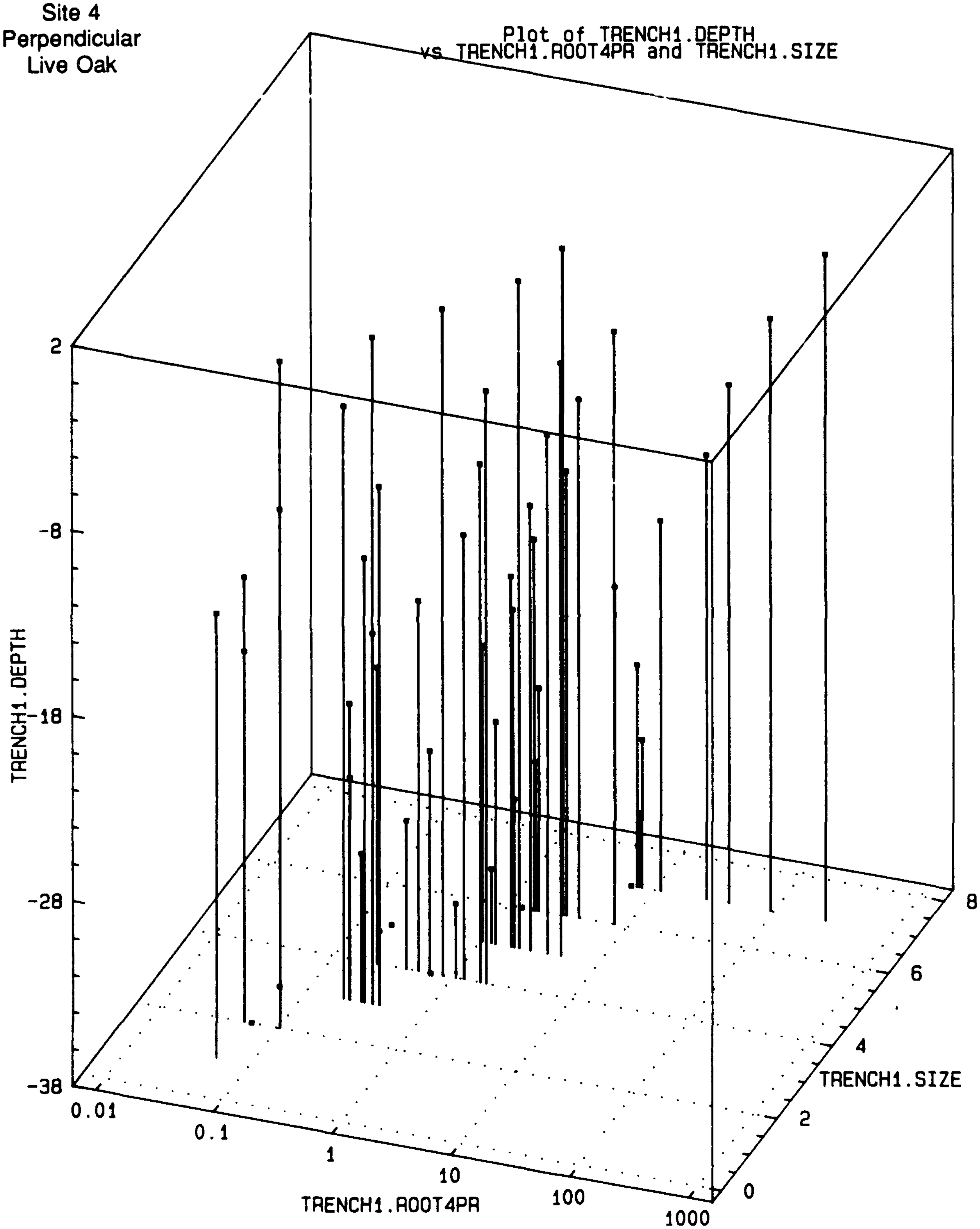
Site 5
Parallel Willow



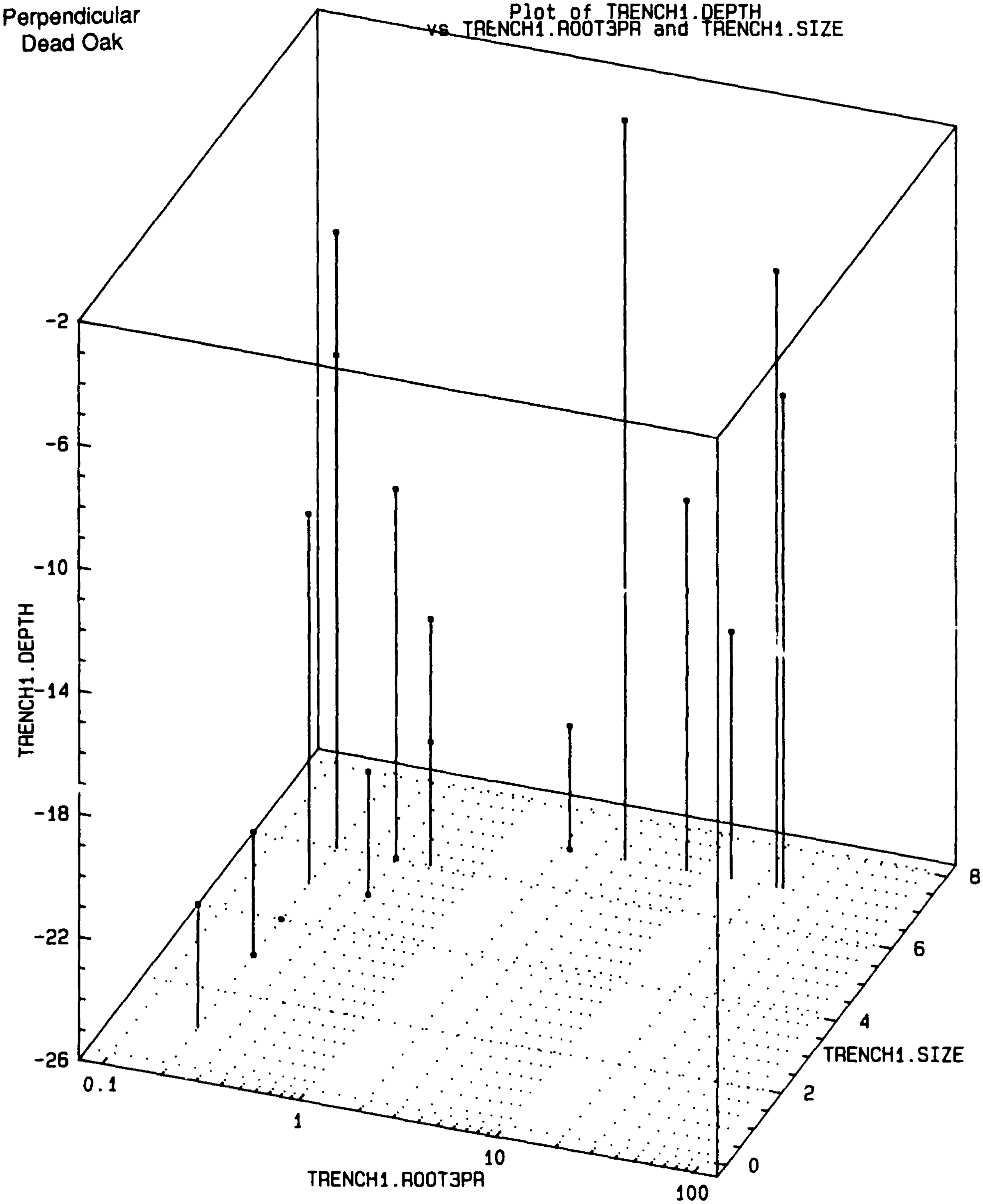
Site 7
Perpendicular



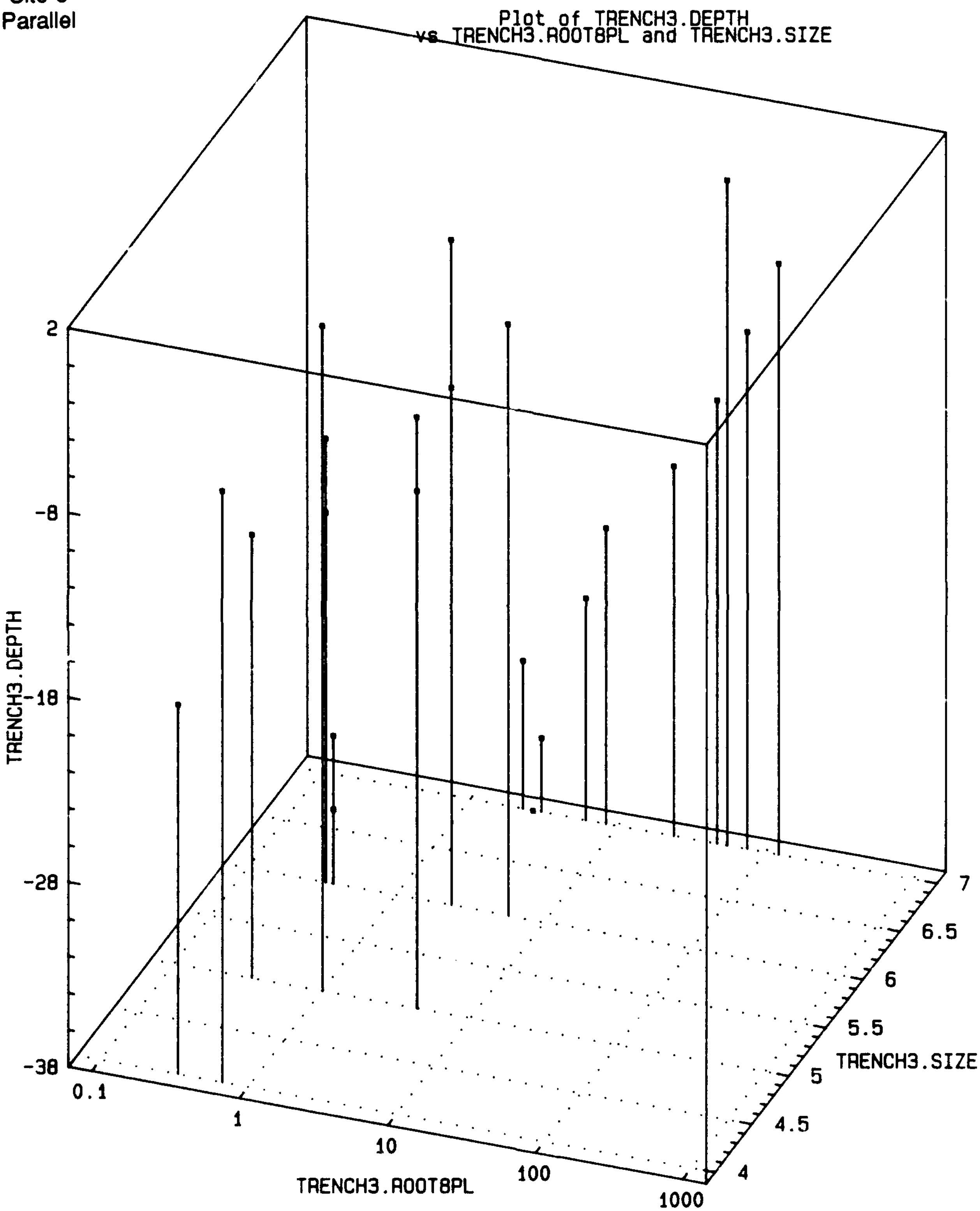
Site 4
Perpendicular
Live Oak



Site 3
Perpendicular
Dead Oak



Site 8
Parallel



Site 8
Perpendicular