WATER RESOURCES BULLETIN
VOL. 28, NO. 5 AMERICAN WATER RESOURCES ASSOCIATION OCTOBER 1992

EFFECTS OF WOODY VEGETATION ON SANDY LEVEE INTEGRITY[1]

F. Douglas Shields, Jr. and Donald H. Gray[2]

ABSTRACT: The influence of woody vegetation on the reliability of a sandy levee was investigated using field data in seepage and slope stability analyses. Field data were collected from selected sites within a 10-km segment of a channel levee on the Sacramento River near Elkhorn, California. Root architecture and distribution were determined using the profile-wall method in which root cross sections were exposed in the vertical wall of an excavated trench. Transects running both parallel and perpendicular to the crest of the levee were excavated at six sites. Each site was dominated by different plant species: five sites were adjacent to trees or woody shrubs, while one supported only herbaceous growth. Lateral plant roots were primarily restricted to, and modified, the near-surface soil horizons to a depth of approximately 1 meter. Root area ratios (RARs) did not exceed 2.02 percent and generally decreased exponentially with depth. At depths greater than 20 cm, mean RARs for sites dominated by wood species were not significantly different from the mean RAR for the herbaceous site. No open voids clearly attributable to plant roots were observed. Roots reinforced the levee soil and increased shear resistance in a measurable manner. Infinite slope and circular arc stability analyses were performed on the landward and riverward slopes under different hydraulic loading conditions. Infinite slope analyses indicated increasing root area ratio from 0.01 percent to 1 percent increased the factor of safety from less than one to more than seven. Circular arc analyses indicated that even the lower measured root concentrations sufficed to increase safety factors for arcs with maximum depths of about 1 m from less than one to about 1.2. Our findings suggest that allowing woody shrubs and small trees on levees would provide environmental benefits and would enhance structural integrity without the hazards associated with large trees such as windthrowing.
(KEY TERMS: erosion; water management; levee; slope stability; vegetation; trees; roots; slope stability; maintenance; riparian vegetation; habitat; riverine corridor; seepage.)

INTRODUCTION

Levees are earthen embankments constructed along rivers to contain floods and are usually subject to hydraulic loading for durations of less than a few weeks annually. Levees are common in many parts of the world. As of 1991, the U.S. Corps of Engineers had constructed 14,000 km of levees along streams in the U.S. (Sullivan, 1992; Anonymous, 1992), and additional levees have been constructed by other agencies and private concerns. About 1,000 communities (5.5 percent of floodprone communities in the U.S.) had levees that protected them from the 1 percent annual probability flood, and the protected area was about 13,000 km^2 (Anonymous, 1992). As in most engineering structures involving soils, levees are normally designed without consideration of effects of vegetation on soil properties (U.S. Army Corps of Engineers, 1978). However, the body of knowledge regarding effects of vegetation on engineered systems is growing (Gray and Leiser, 1982; Gray, 1991). Effects of woody vegetation on levee integrity has been a subject of sharp debate in some circles. Although European practice has included provisions for allowing large trees on certain levees (Keller and Brookes, 1984), federal standards in the U.S. prohibit vegetation other than grass (Code of Federal Regulations, Title 33, Section 208.10; U.S. Army Corps of Engineers, 1968):

> 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.

The "where feasible" clause has allowed exceptions in semi-arid regions where sod requires irrigation. However, even in these cases, vegetation is officially

[1]Paper No. 92082 of the *Water Resources Bulletin*. **Discussions are open until June 1, 1993.**
[2]Respectively, Research Hydraulic Engineer, USDA-ARS National Sedimentation Laboratory, P.O. Box 1157, Oxford, Mississippi 38655-1157; and Professor, Department of Civil Engineering, University of Michigan, 2340 G. G. Brown Bldg., Ann Arbor, Michigan 48109-2125.

limited to herbaceous (i.e., non-woody) species, and is cut or burned regularly. Despite the regulations, many levees are not maintained according to federal standards (Davis *et al.*, 1967; Gray *et al.*, 1991).

The rationale for the current standard is based on proven and hypothetical hazards: vegetation must be limited to indirectly control burrowing rodents; access to levee slopes during floods must be unimpeded for flood-fighting; levees with large vegetation are harder to inspect visually; large trees may be subject to windthrow or may create flow patterns that scour slopes; roots may facilitate initiation of piping during floods; and uprooting of large trees during storms can remove enough soil from the embankment to initiate failure. The effect of levee slope vegetation on burrow density has been investigated, but different investigations have produced conflicting results (Salmon *et al.*, 1987; Fitzgerald and Marsh, 1986; Daar *et al.*, 1984; Owings *et al.*, 1977). Flood-fight access may be safeguarded by vegetation guidelines that prohibit dense stands of large trees but allow "shrubbier" species (both woody and herbaceous). Policies can be devised to preserve travel ways and openings in stands of larger vegetation. Inspection is a question of resource allocation. Even heavily vegetated levees may be inspected given adequate time and manpower (Hynson *et al.*, 1985), and communities may decide environmental benefits of vegetation on levees are worth additional expense. Root-induced piping has not been documented scientifically, but has been described anecdotally by several writers (Nolan, 1981; Tschantz and Weaver, 1988). Although earthen embankments such as levees undoubtedly have failed due to piping (e.g., Cedergren, 1967), fissures, cracks, and macropores (elongate voids with diameters along their minor axes an order of magnitude or more larger than soil particles) not due to roots may have been the cause of piping rather than holes along roots (Sherard, 1986; Gray *et al.*, 1991). Furthermore, some investigators have documented beneficial effects of vegetation on performance of embankments subjected to extreme loadings. For example, Gilbert and Miller (1991) studied 26 cases of documented embankment overtopping and concluded that vegetation cover increased erosion resistance of the downstream slope by providing a protective cover and by increasing apparent cohesive strength by root reinforcement. Vegetation types for the case studies they reported were usually not specified; however, their accounts indicate a cover of sod.

Physical benefits of vegetation larger than sod include erosion control, reduced maintenance costs, and enhanced slope stability. Slope stability is enhanced due to soil reinforcement by roots (Sidle, 1991), and, at least in some environments, woody vegetation offers better protection than herbaceous (Davidson *et al.*, 1991). Furthermore, vegetation larger than sod along a river corridor can provide considerable wildlife habitat and aesthetic benefits (Dennis *et al.*, 1981; Nunnally *et al.*, 1987). Thus, this paper presents analyses of the effects of several types of vegetation on stability of sandy levee slopes. Issues related to root-induced piping are not directly addressed. The purpose of this paper is to provide initial results which, when coupled with additional work, may lead to modified levee vegetation standards.

Data obtained from a sandy levee along the Sacramento River 20 km northwest of Sacramento, California, allowed description of levee geometry, geotechnical properties, vegetation cover, and belowground root densities and distributions for sites adjacent to large trees, woody shrubs, and stands of herbaceous vegetation free of woody species. These data were used in seepage and mass stability analyses to assess effects of woody and herbaceous plants on levee integrity.

STUDY AREA

A 10-km segment of a sandy levee on the west bank of the Sacramento River about 15 km downstream of the mouth of the Feather River near Elkhorn, California (Figure 1), was selected for detailed study. The levee was not a result of engineering design, but was built between 1912 and 1916 by hydraulic fill using material dredged from the river channel. The levee embankment was about 4 m high with a 6 m wide crest topped with an unpaved road. A relatively flat berm 8-30 m wide separated the riverward toe and the top of the bank. The landward slope was steeper and generally more xeric than the riverward slope and supported less vegetation. The riverward slope supported more or less monospecific clumps of native and introduced riparian vegetation. Dominant woody species on both slopes included valley oaks (*Quercus lobata*) and cottonwood (*Populus fremontii*); herbaceous species included mixed grasses and sedges, storksbill (*Erodium* sp.) and horsetail (*Equisetum* sp.). Several groups of mature, > 30-year-old cottonwoods and valley oaks were on the riverward slope as well as smaller black locusts (*Robinia pseudoacacia*), shrubby willows (*Salix* sp.), and wild rose (*Rosa californica*). Vegetation was suppressed by periodic (at least annual) burning. California ground squirrel (*Sphermophilus* sp.) burrows were ubiquitous in the levee.

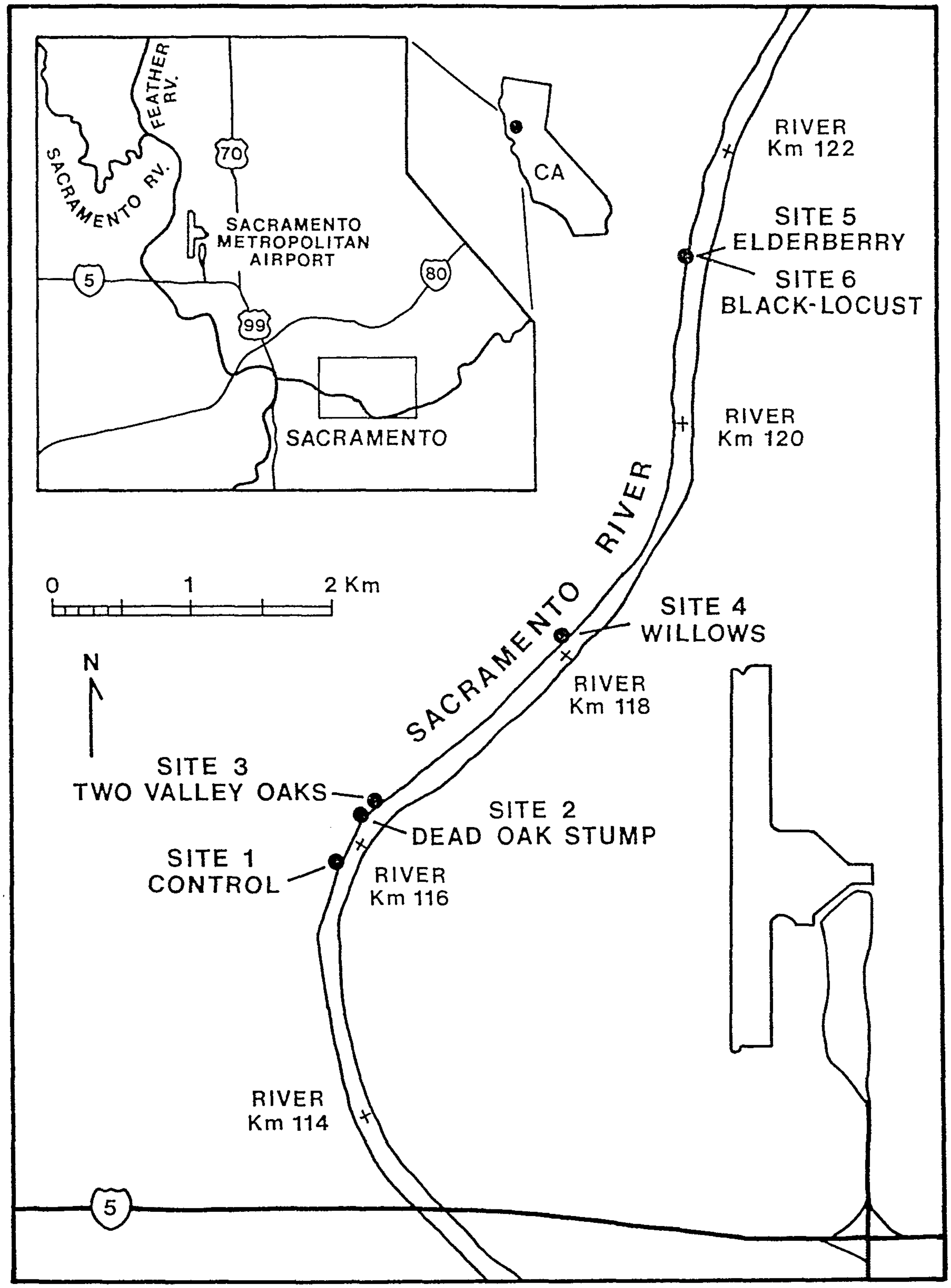


Figure 1. Location of Study Area and Study Sites.

METHODS

Physical and botanical data were collected at six sites on the riverward slope of the study area levee (Figure 1 and Table 1). Sites were selected to reveal soil properties underneath stands of five of the most common woody species and underneath a control area that supported only herbaceous vegetation. Levee cross sectional geometry was determined at each site using surveying instruments.

Detailed soil and botanical investigations were concentrated about an L-shaped line laid out on the riverward levee slope at each site. Limbs of each L ran parallel and perpendicular to the levee crest. At the valley oak, willow, and black locust sites, the arms of the L were tangent to the dripline or crown edge of the woody plants of interest. At the elderberry bush site the perpendicular limb was routed through the center of the clump of elderberry bushes, but the parallel limb was tangent to the crown edge.

Soil Properties

Soil samples were collected along the L at 15 cm vertical intervals to a depth of 1.2 m using a 5 cm diameter bucket-type auger. Samples were returned to the laboratory and subjected to grain size (ASTM D422-58) and permeability (gas permeameter) analyses (American Society for Testing Materials, 1985). Permeabilities were measured on dry samples reconstituted in the laboratory to different relative densities (void ratios) in order to determine a permeability-void ratio relationship from which field permeabilities could be estimated. Shear strength parameters (friction and cohesion) were determined *in situ* at the same locations along the L where soil samples were collected using an Iowa borehole, direct shear device (Wineland, 1975; Handy, 1986). In some cases it was necessary to prewet the sandy levee soils to prevent borehole collapse during direct shear testing. In order to facilitate measurement of root sizes and spatial distributions, a narrow, 1.2 m deep trench was excavated at each site using a backhoe. The interior wall of the trench followed the previously mentioned L-shaped line. Soil densities were measured by collecting samples from trench walls with an Eley volumeter adjacent to the holes augered for grain size samples and direct shear measurements.

Botanical (above-ground) Surveys

Vegetation on the levee crest and both slopes throughout the 10 km long study area was surveyed to determine typical species composition and cover. Seventeen 1 m wide quadrats (rectangular plots) running from the landward levee toe to the riverbank at right angles to the crest were selected at random along the study area levee. Boundaries of each quadrat were marked on the ground, and vegetative cover within each quadrat was mapped. Vegetation was identified to the genus or class level, and categorized as trees, shrubs, or ground cover. At the six study sites, vegetation growing within a 2 m wide

TABLE 1. Study Sites for Collection of Physical and Botanical Data on Woody Vegetation, Sacramento River Levee.

Site No.	River Kilometer	Dominant Vegetation		Remarks
		Common	Species	
1	115.6	California Rose	*Rosa californica*	Used as "control."
2	116.2	Dead Stump	*Quercus lobata*	Tree was cut 5-13 years before this study. The age of tree when cut was ~ 37 years.
3	116.3	Valley Oaks	*Quercus lobata*	Trenches* were located at dripline of two closely-spaced trees, each about 0.7 m in diameter.
4	118.1	Willows	*Salix hindsiana*	Trenches were at dripline.
5	121.2	Elderberry	*Sambucus mexicana*	Parallel trench was at dripline; perpendicular trench went through center of clump of elderberry-bushes.
6	121.2	Black Locust	*Robinia pseudoacacia*	Trenches were at dripline.

*Trenches were excavated to sample roots.

strip that extended 1 m on either side of the L-shaped line was inventoried prior to trenching.

Botanical (below ground)

The profile wall method (Bohm, 1979) was adapted for determining below ground plant characteristics at all sites. At Site 2, the partial excavation method (Bohm, 1979) was also used to reveal root architecture of a single dead oak stump. The profile wall method consists of excavating a narrow trench to reveal roots and then mapping roots that are visible on the vertical trench wall. Trenches were constructed with care to avoid disturbing roots and surrounding soils. Trench sites were soaked with water from a tank truck prior to excavation to prevent trench caving. A pruning saw was run along the flagged L-shaped line prior to trenching to cut surface roots to a distance 20-25 cm below the surface, thus limiting disruption of the mapping face by root breakage during backhoe excavation. Trenches were excavated using a backhoe, but the bucket was kept at least 15 cm away from the mapping face, and large diameter roots exposed but not readily broken by the backhoe were cut manually. Soil remaining after backhoe excavation was trimmed back to the mapping face using hand tools. Root locations and sizes were mapped on an acetate overlay held in place by a tubular frame placed against the trench face (Gray *et al.*, 1991). Presence of voids, macropores, mineral inclusions (rocks, clay balls, etc.) and gross stratigraphic gradients were noted as well as root locations and sizes.

Geotechnical Analyses

Field data and appropriate parameter values from literature were used to perform seepage and mass stability analyses (Table 2). Conservation assumptions were made when measured data were unavailable. For example, a standard geometry was used for the levee cross section that was slightly smaller than the observed cross sections, which were not uniform. The free water level on the riverward side of the levee was set at 90 percent of the levee height for seepage analyses. The maximum stage on record in the study area reached about 80 percent of the levee crest height, but only for a short segment of the levee (the crest elevation of the levee was quite irregular). Soils underneath the levee embankment were assumed to be impervious, which was conservative in light of available information regarding their composition (Water and Engineering Technology, Inc., 1989).

Seepage analyses were run assuming steady hydraulic conditions. As noted above, water surface elevation on the riverward slope was assumed to correspond to an elevation equivalent to 90 percent of

TABLE 2. Values of Key Parameters Used in Geotechnical Analyses.

			Seepage		Mass Stability	
Category	Parameter	Field Data	Transient	Steady State	Infinite Slope	Circular Arc
Geometry	Crest Width, m	6.1	6.1	6.1	n/a	n/a
	Landward Slope	2H:1V	2H:1V	2H:1V	2H:1V	2H:1V
	Riverward Slope	>3H:1V	2H:1V	3H:1V	3H:1V	3H:1V
	Embankment Height, m[a]	4	4	6.1[b]	4	4.6[b]
Soil Properties	Dry Density, $kg\ m^{-3}$	1,360-1,470	1,440[c]	n/a[d]	1,440[c]	1,440[c]
	Permeability, $cm\ sec^{-1}$	0.03-0.07	0.05[c]	n/a	n/a	n/a
	Friction Angle, deg	28-36	n/a	n/a	28 or 31.6[e]	30
	Cohesion, $kg\ cm^{-2}$	0-018	n/a	n/a	0 or 0.084[e]	0.23 x RAR
Botanical	RAR, percent	0.001-2.02	n/a	n/a	0-2[e]	0.13-0.001d[f]
Hydraulic Loading	Duration, hr	15	computed	n/a	See Below[g]	
	Elevation, m[a]	3.2	3.2	3.6	See Below[g]	

[a]Above landward toe.
[b]Embankment height selected to facilitate calculations.
[c]Mean of field observations.
[d]n/a = not applicable.
[e]Minimum and mean of field observations.
[f]d = depth below surface in cm. Equation is based on regression of data from parallel trench at Site 5 and is representative of conditions at drip line of a clump of woody shrubs.
[g]Sudden drawdown or "parallel" seepage conditions.

the embankment height above the landward toe; the water surface elevation on the landward side was assumed to be at the toe. The validity of this assumption for the landward side of the study site was checked using a method presented by Huang (1986) to compute the time required for a phreatic surface to reach the landward levee toe, given the stage hydrograph for the flood of record (February 1986), and assuming a homogenous levee embankment free of conduits or pipes. Profiles of the study area levee crest elevation and flood peak elevations derived using unsteady flow simulation were obtained from the Sacramento District of the U.S. Army Corps of Engineers (SD). Flood peak durations were assumed to match those recorded by a gaging station at river kilometer (RK) 127.2. There were no major inflows, outflows, or changes in channel geometry between the study area and the gage. Stage hydrographs (hourly data) from the RK 127.2 station for the flood of record were also provided by the SD.

Two-dimensional seepage analyses were performed in a spreadsheet using a relaxation technique to solve finite difference equations for the flow net. Nodes for computations were spaced at 0.3 m intervals. Effects of vegetation on seepage were simulated by assuming that a vegetated levee was composed of a homogenous core covered by a 0.3 m thick layer modified by root biomass. The thickness of the modified layer was based on botanical results presented below. Plant cover generally increases the permeability of surface soils, but in some situations (e.g., where a dense ground cover traps wind-blown fines), plant cover could cause a reduction in permeability. Therefore equipotential lines (flow nets) were computed and plotted for three cases: a homogenous levee, one with a surface layer 10 times more permeable than the core, and one with a surface layer 10 times less permeable than the core. These differences in permeability represent our perception of the possible extremes rather than likely typical values.

Mass stability analyses were performed using infinite slope and circular arc models (Huang, 1983). Infinite slope analyses were used to assess potential for planar slides with failure surfaces parallel to the slope (shallow sloughing). Circular arc analyses were used to assess potential for rotational sliding along a shallow curved surface passing through the toe of the slope. Soils were assumed to be saturated below the phreatic surface and completely dry above it. The influence of vegetation was investigated by increasing the soil cohesion values near the ground surface to reflect measured root densities as follows:

1. Dimensionless root densities were computed by dividing the area of the trench wall by the cross-sectional area occupied by roots and expressing as percent [hereinafter referred to as the root area ratio (RAR)].

2. The field data (root density values) were used to develop regression equations for RAR as a function of depth below surface.

3. RARs predicted using the regression equations were then used to compute an equivalent cohesion using the relationship:

$$c_R = 0.23 \times RAR$$

where c_R = soil shear strength due to roots (root cohesion) in kg (force) cm^{-2}; 0.23 = coefficient based on an assumed density for roots of 640 kg m^{-3} and the mean of published shear strength measurements and root biomass concentration for sand soils (Gray and Ohashi, 1983; Ziemer, 1981); and RAR = root area ratio, percent. Factors of safety based upon the circular arc model were computed using a modified method of slices procedure (VonGunten, 1984).

RESULTS

Levee Geometry and Soils

Levee geometry was less uniform than for more modern embankments. Landward slopes of the levee embankment closely matched the 2H:1V landward slope of the standard design section, but riverward slopes were slightly less steep than the 3H:1V standard and were not uniform.

Levee soils were fairly uniform, medium to fine sands (SP) with little to no silt or clay. Trenching revealed little internal stratigraphy within levee embankments. Fine soils usually occurred as inclusions smaller than about 20 cm diameter or discontinuous layers less than 10 cm thick. Median grain sizes were generally between 0.2 and 0.4 mm. Average dry density (all samples) was 1,440 kg m^{-3}; site averages ranged from 1,360 to 1,470 kg m^{-3}. Permeabilities of sand specimens reconstituted to densities within this range of field dry densities ranged from 0.03 to 0.07 cm sec^{-1}, and were linearly related to the square of the void ratio as predicted by the Kozeny-Karman relationship. Mean values of friction angle and cohesion determined from Iowa bore hole tests were 31.6 ± 3.7 degrees and 0.084 ± 0.043 kg cm^{-2}, respectively. Cohesion and friction angle were inversely correlated ($r = -0.645$). Average site cohesion and average site density were directly correlated because soils with higher silt-clay contents were denser. Effects of root reinforcement were manifest as bilinear failure envelopes in some of the bore hole shear results, i.e., plots of shear stress versus normal stress approximated two distinct line segments with the steeper segment for low normal stress. Bilinear or curved-linear failure envelopes are typical of fiber-reinforced sands (Gray and Al-Refeai, 1986; Maher and Gray, 1990).

Voids and pedotubules exposed in the trench face were mapped along with roots. A pedotubule is a relict conduit or biopore that has been infilled by soil washed in from the surrounding matrix. Voids created by burrowing rodents and insects were observed at all depths, but no voids clearly attributable to decayed or rooted roots were observed. In a few cases pedotubules consisting of residual bark linings filled with soil were observed. Mean void densities (number of voids x m^{-2}) were computed for each 10 cm depth increment at each site. Densities of voids larger than 5 mm diameter ranged from 0 to 9.7 m^{-2}, and averaged 1.65 m^{-2}. At most sites, the maximum density of voids > 5 mm occurred between 10 and 20 cm below the surface. Mean density of voids > 5 mm (averaged over the entire depth) for the elderberry clump, herbaceous (control), and woody dripline sites were 5.07, 1.82, and 1.54 m^{-2}, respectively. Voids at the valley oak site were larger and less numerous than for the elderberry site, evidently because the former site had more ground squirrel activity, while the latter had more insect activity.

Botanical – Above Ground

Means of cover data from the 17 randomly-located quadrats aligned at right angles to the levee crest were assumed to represent average conditions for the study area. Little grew on the landward slope during the sampling period (October through early March), but lush vegetation developed after late winter rains and warmer temperatures coincided in mid- to late March. More tree cover occurred on the riverward slope than on the crest or landward slope (Table 3). Valley oak (*Quercus lobata*) was ubiquitous throughout the study area. Cottonwood (*Populus fremontii*) was common on the riverward slope. Herbaceous plants reflected effects of seasonal weather patterns and periodic burning, which was a routine maintenance practice. Herbaceous cover was depressed due to burning at several locations within the study area. Licorice (*Glycyrrhiza* sp.) was well adapted to the levee environment and to burning, resprouting vigorously after fires.

Tree cover at the six study sites averaged 42 percent (percent of ground surface underneath canopy), which was much higher than for the riverward slope average (11 percent) (Figure 2 and Table 3). This difference occurred because the trench sites (except for the herbaceous and the dead stump) were chosen to be within woody canopy. Vegetation at three of the sites (dead oak stump, willow, and elderberry) had been burned, and ground cover was depressed accordingly. Cover due to shrubs and ground cover at the herbaceous (control) site was 16 percent higher than the average for the riverward slope, but was closer to the value for the landward slope, which had only 0.44 percent tree cover. Species at the herbaceous (control) site included various grasses and sedges (23.5 percent of absolute cover), California rose (*Rosa californica*, 31.6 percent), telegraph weed (*Heterotheca grandiflora*, 1.5 percent), and lotus (*Lotus purshianus*, 0.2 percent).

TABLE 3. Vegetative Cover on Levee Slopes in Sacramento River Study Area, Percent.

Site Description	Site Number	Trees*	Shrubs	Ground Cover
Control	1	0.0	33.3	23.5
Dead Oak Stump	2	0.0	0.0	0.0
Valley Oaks	3	~99	24.0	0.1
Willows	4	~10	0.0	0.0
Elderberries	5	72.0	5.4	0.0
Black Locust	6	72.4	2.5	0.0
Mean for Trenches	1-6	42.0	11.0	4.0
Riverward Slope	Entire	11.0	0.1	40.4
Crest	Study	0.15	0.0	36.7
Landward Slope	Area**	0.44	0.08	48.1

*Percent of ground surface underneath canopy.
**Means from 17 1-m wide quadrats located randomly along 10 km study area.

Botanical – Below Ground

RARs were computed for each limb of each L-shaped trench by 10 cm depth increment (Table 4). Observed RARs varied from 0.001 to 2.02 percent and averaged 0.17 percent (std. dev. = 0.30 percent). The maximum RAR was observed in the top 10 cm of soil at the herbaceous (control) site, and was largely due to the presence of one 11.5 cm diameter root found in the top 10 cm of soil; the RAR computed without this root would have been 0.11 percent. Since mean RARs for the four sites that had both trenches at woody driplines were not significantly different (α = 0.96, ANOVA), the RAR data were placed into three groups to facilitate comparison: herbaceous (Site 1), woody driplines and the dead stump (Sites 2-4 and 6), and the trench through the center of the elderberry clump (Site 5) (Figure 3 and Table 5). RAR summed over all depths, was greatest for the trench through the center

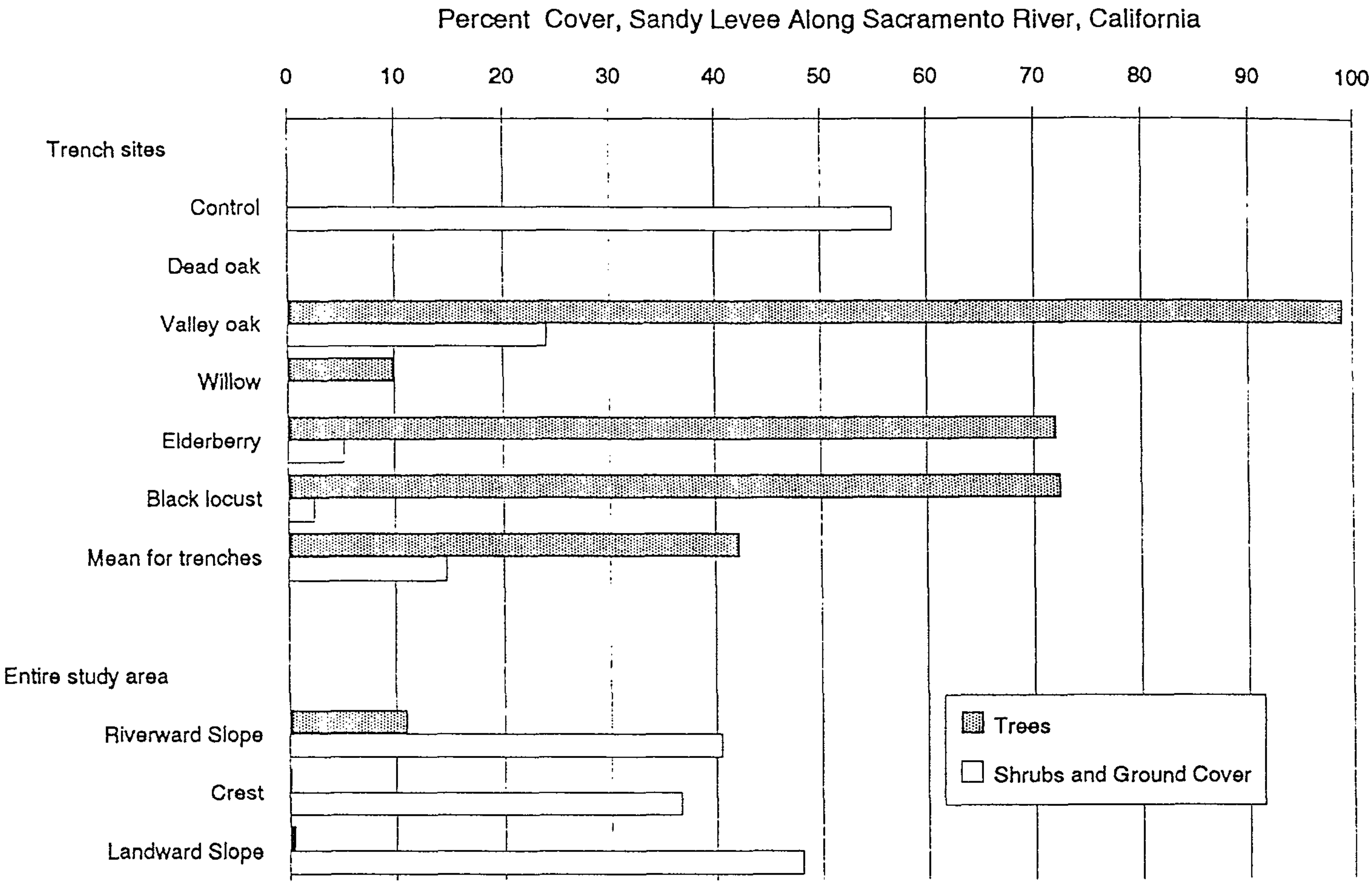


Figure 2. Vegetative Cover for Entire Study Area and for Trench Sites.

TABLE 4. Root Area Ratios in Percent by Depth Increment and Trench Orientation for Each Site, Sacramento River Levee.

Depth, cm		Herbaceous (control) Site 1		Dead Stump Site 2		Valley Oaks Site 3		Willows Site 4		Elderberry Site 5		Black Locust Site 6	
From	To	Para.[a]	Perp.	Para.	Perp.	Para.	Perp.	Para.	Perp.	Para.	Perp.	Para.	Perp.
0	10	2.02	0.10	0.04	0.001	0.32	0.01	0.03	0.20	0.16	0.50	0.03	0.85
10	20	0.02	0.62	0.02	0.01	0.23	0.04	0.10	0.18	0.11	0.55	0.12	0.07
20	30	0.01	0.18	0.40	0.01	0.28	0.01	0.36	0.26	0.08	1.11	0.07	0.62
30	41	0.10	0.12	0.11	0.003	0.25	0.01	0.01	0.20	0.05	0.78	0.02	1.02
41	51	0.19	0.01	0.04	0.01	0.15	0.02	0.01	0.10	0.06	0.42	0.02	0.87
51	61	ND[b]	0.06	0.03	0.01	0.06	0.12	0.01	0.05	0.17	0.33	0.002	0.01
61	71	ND	0.39	1.06	0.001	0.09	0.02	0.01	0.03	0.05	0.18	0.001	0.02
71	81	ND	0.06	0.004	0.03	0.09	0.04	0.01	0.004	0.11	0.07	0.001	0.13
81	91	ND	0.10	0.09	0.24	0.13	0.02	0.001	0.06	0.03	0.12	0.001	0.01
91	101	ND	0.15	0.001	0.16	0.08	0.13	0.004	0.34	0.01	0.07	0.001	0.001
Mean (S.D.)		**0.28 (0.51)**		**0.11 (0.24)**		**0.11 (0.10)**		**0.10 (0.12)**		**0.08 (0.05)[c]**		**0.19 (0.34)**	

[a]Trench Orientation: Para. = Parallel to levee crest, Perp. = perpendicular to levee crest.
[b]ND = No data.
[c]For parallel trench only. Mean RAR for perpendicular trench, which was aligned through the center of the elderberry clump, was 0.41 ± 0.34.

D-030781

D-030781

TABLE 5. Mean RAR for Study Sites Grouped by Vegetation Type and Trench Location.

Group	For All Depths			For Depths > 20 cm		
	n	Mean	S.D.	n	Mean	S.D.
Herbaceous (control)	15	0.28	0.51	11	0.12	0.11
Woody Driplines and Dead Stump	80	0.13	0.22	64	0.12	0.23
Elderberry Clump	10	0.41	0.34	8	0.39	0.38

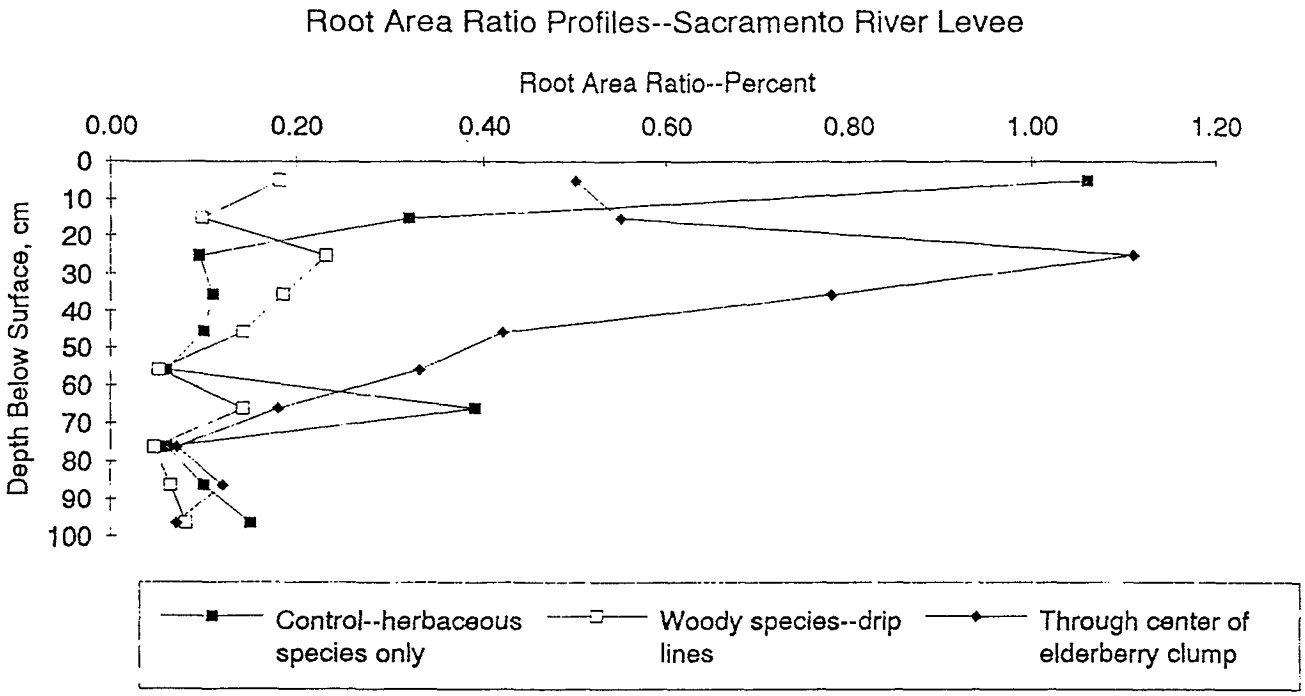


Figure 3. Variation of Root Density with Depth Below Ground Surface.

of the elderberry clump. Although ANOVA indicated that the mean RAR for the herbaceous site was different from the mean for woody dripline sites at α = 0.07, the mean RARs for soil layers deeper than 20 cm were not significantly different (α = 0.997) (Table 5).

Mean RAR generally decreased with increasing depth below the surface, but this trend was much more pronounced for the herbaceous and elderberry clump sites (Figure 3). In order to facilitate comparison of our results with others (e.g., Sims and Singh, 1978) we computed regression coefficients for the equation $y = ax^b$ where y is the RAR for a given depth interval and x is the midpoint of the depth interval in cm (Table 6). Our exponential coefficients ("b") were similar to those reported by Sims and Singh (1978) for eight western North American grassland sites. Using root biomass as the dependent variable rather than RAR, they computed exponents ranging from –0.191 to –1.06. However, our data indicated a weaker dependence of RAR on depth than reported by Sims and Singh (1978): 13 of the 16 regression equations they presented had $p \leq 0.077$.

The average number of roots per square meter of trench wall (root density) at each site was computed for seven root size categories. Results are summarized in Figure 4. Root density decreased exponentially with root size regardless of vegetation type (smaller roots were more common). Mean density of roots smaller than 0.1 cm was 90 percent greater for the woody dripline sites than for the herbaceous (control) site. Presumably, larger roots at greater depths pose more of a potential piping hazard than fine roots at shallow depths. In our study, large roots were rate, particularly at depth: no roots larger than 2 cm diameter were found below 45 cm at the herbaceous site. Frequency of roots 2-3 cm in diameter and larger than 3 cm at the woody dripline sites averaged 0.14 and 0.16 m^{-2}, respectively, for depths below 45 cm.

The orientation of roots was studied to determine how thoroughly roots reinforced the sandy levee embankment. Most of the roots of herbaceous materials were oriented vertically, but the roots were short. Roots from elderberries and willows were distributed hemispherically about the root crown. Oak roots mapped at the valley oak site were lateral, and were distributed subparallel to the ground surface. The root architecture of the dead oak stump was characterized by a massive central tap root (~ 0.4-0.2 m diameter) 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. Most of these lateral roots angled down sharply (< 30 degrees from the vertical) rather than growing out in a quasi-horizontal attitude characteristic of lateral roots. Perhaps this pattern was due to the extremely droughty conditions within the sandy levee embankment.

Geotechnical Analyses

Stage hydrographs and flood peak profiles indicated that the flood of record (February 1986) inundated the riverward levee slope at the study sites up to an elevation 3.2 m above the levee base, or about 0.8 times the levee height, for about 15 hours. The method described by Huang (1983) for plotting the unsteady state phreatic surface in earth dams as a function of time yielded an estimate of 11 hours for the phreatic surface to reach the landward toe. However, this value is conservatively low because the upstream slope in the Huang method is assumed to be only 2H:1V rather than 3H:1V (Table 2). Nevertheless the assumption of steady conditions for the seepage analysis appears to have been valid. Through seepage was observed at the site during a flood prior to our

TABLE 6. Variation of Root Area Ratio with Depth Below Levee Surface Results of Nonlinear Regression – RAR = a * (depth in cm)^b.

	n	a	b	r^2	t	p*
Herbaceous (control)	15	6.25	–1.15	0.39	2.88	0.01
Woody Driplines and Dead Stump	80	0.30	–0.24	0.03	1.29	0.20
Elderberry Clump	10	1.18	–0.29	0.21**	1.47	0.18

*Probability that correlation is due to change.

**An r^2 of 0.53 (p = 0.02) was computed for a regression equation of the form RAR = a exp (–b * depth).

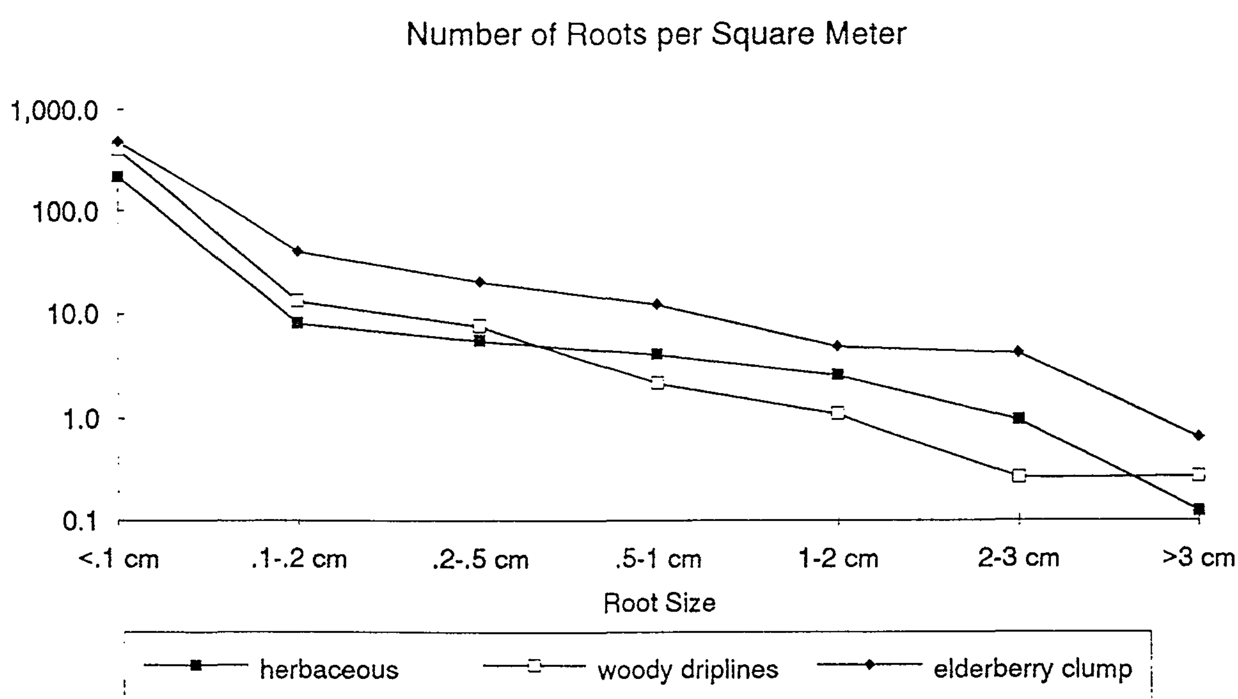


Figure 4. Number of Roots Per Square Meter of Trench Wall by Root Size Class.

study, and seepage through the embankment slightly upstream from the site was sufficient to require placement of a seepage blanket.

Dividing or multiplying soil permeability by 10 for the top 0.3 m of the levee surface had little effect on seepage (equipotential lines, phreatic surface location) on the riverward slope. However, on the landward slope, a surface layer 10 times less permeable than the core elevated the phreatic surface and increased the discharge area on the slope. This condition could lead to decreased mass stability and increased danger of seepage erosion, especially in a sandy embankment (Gilbert and Miller, 1991).

Infinite slope analyses were performed for landward and riverward slopes using a range of assumed seepage directions, root densities, and soil friction angles. Depth to failure surface was varied from 0.10 m to 5 percent of the slope length (0.4 and 0.6 m for 2:1 and 3:1 slopes, respectively), and RAR was not varied with depth. Factors of safety were lower for the steeper (2:1) slope. The variation in safety factor with RAR for conditions where seepage direction paralleled the slope is presented in Figure 5 for average (soil friction angle = 31.6 deg, cohesion = 0.084 kg cm^{-2}) and worst case (soil friction angle = 28 deg. cohesion = 0.0) conditions. Safety factor increased with increasing RAR. Effects of roots were more pronounced for worst case conditions (Figure 5a). For worst case conditions, an increase in RAR from 0.01 to 1.0 percent increased the landward slope factor of safety 40 cm below the surface from 0.6 to 8.8. Increasing RAR tended to increase the critical depth (the critical depth is where safety factor = 1). Results for the riverward slope were similar: for worst case conditions, an increase in RAR from 0.01 to 1.0 percent increased the factor of safety 60 cm below the surface from 0.8 to 7.7.

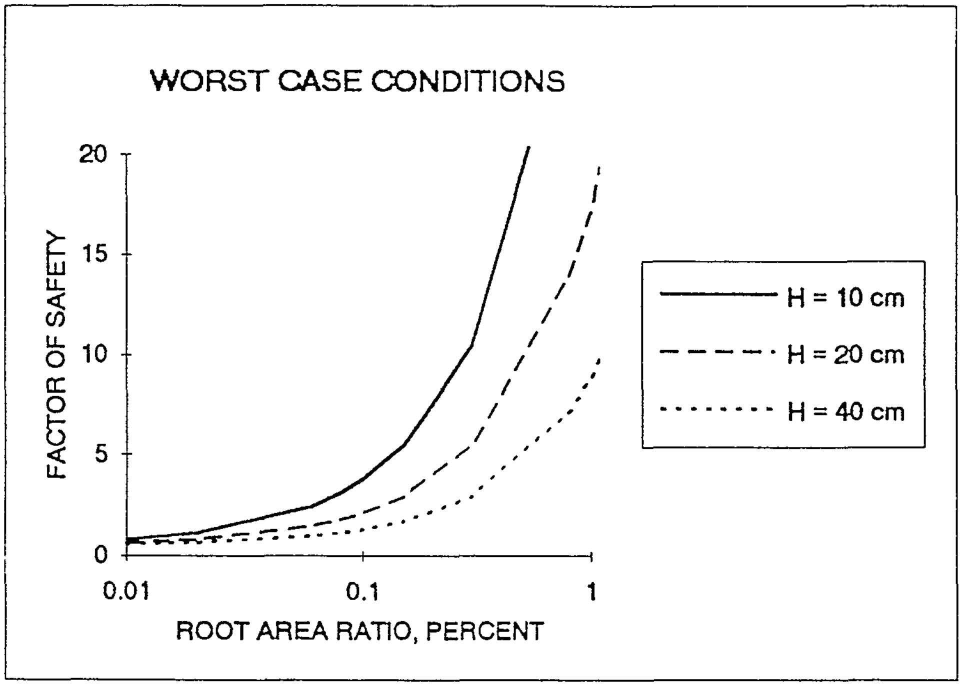
Circular arc analyses were performed for both 2:1 and 3:1 slopes for cases with and without the influence of roots. Steady seepage conditions were analyzed for the landward (2:1) slope. RAR was assumed to be either zero or a weakly linear function of depth below the surface (RAR = 0.13 – 0.001 x depth in cm). This function was derived by regressing RAR data from the elderberry parallel trench (Site 5) and was assumed to represent conditions at the dripline of a clump of large, woody shrubs. Results of the circular arc analyses are shown in Figure 6. Root-induced cohesion made an important contribution to slope stability. Without roots, safety factors for both slopes were less than unity for critical shallow failure arcs at depths of less than 1 m. With roots, safety factors ranged from 16.5 (for very shallow failure arcs with maximum depths of approximately 5 cm on the riverward slope) to about 1.2 at 1 m maximum depth on both slopes. The influence of roots on safety factor was greatest near the surface and declined sharply with depth.

DISCUSSION AND CONCLUSIONS

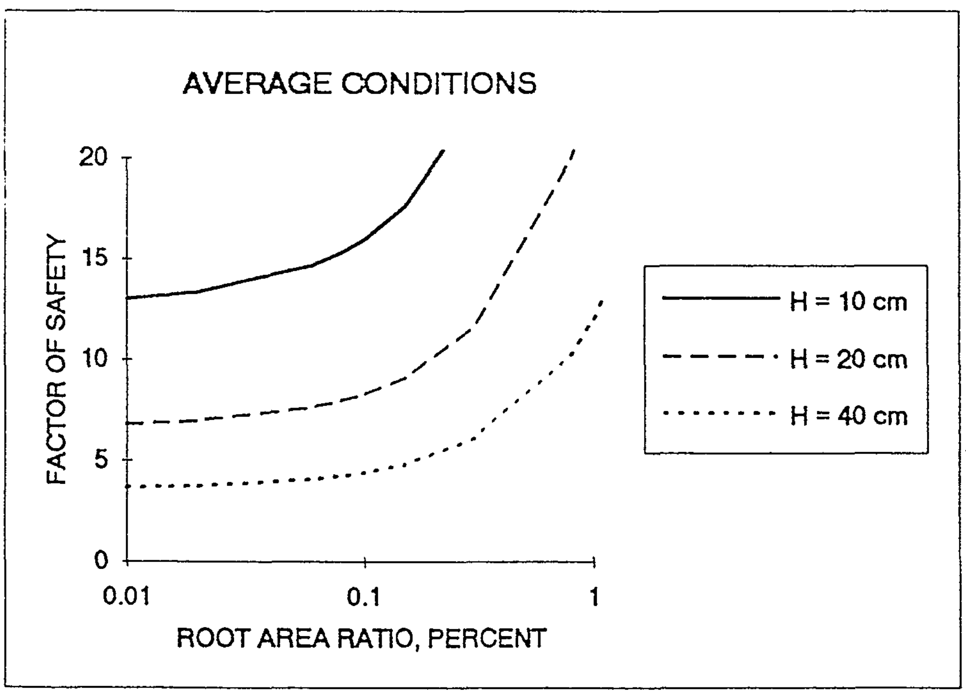
Vertical distribution of roots in the sandy levee may have reflected site adaptation. The disappearance of roots with depth we observed was more gradual than reported by Sims *et al.* (1978), for western grasslands: they found, on average, 30-64 percent of below ground biomass occurred in the top 5 cm of soil, 80 percent in the top 30 cm, and an additional 10-12 percent between 30 and 50 cm. Davidson *et al.* (1991), reported vertical distributions of Minnesota and Wisconsin hillslope root biomass reflected soils and plant types: root penetration was deeper for sandy soils, and below wooded sites 50 percent of root mass was in the top 10 cm, while 90 percent of root mass below herbaceous cover was in the top 10 cm. We found, on average (all trenches except for elderberry clump), 43 percent of root area in the top 30 cm, and an additional 24 percent between 30 and 50 cm. At the herbaceous (control) site, 50 percent of root area was in the top 30 cm and 58 percent in the top 50 cm.

Root area ratios computed from profile wall samples are indicative of root distributions in vertical planes, but root distributions across major slip surfaces are more important for slope stability. Reistenberg and Sovonick-Dunford (1983) presented root area profiles for ash and maple trees growing in a colluvial layer of soil on a steep, slide-prone based on horizontal plane samples. Their data were quite similar to those presented herein. Nevertheless, the pattern of downward-angling lateral roots observed at the dead stump raises questions regarding spatial distributions of tree roots. Perhaps the relative paucity of large roots exposed at the tree driplines is due to the adaptation of the trees to the extremely droughty, sandy levee soils. Lateral roots evidently angled down to reach ground water. Since vertical roots are more likely to be effective in directly resisting downslope shearing forces on surfaces oriented parallel to the slope, the beneficial effects of roots on slope stability described herein may be smaller than benefits actually realized at the study sites. Coppin and Richards (1990) describe slope stabilization due to anchoring, buttressing, and soil arching caused by tree roots.

Woody vegetation has been kept off of earthen embankments because of the potential for piping to initiate along living or dead roots. Although voids due to activities of insects and burrowing rodents were observed at all depths, voids clearly attributable to plant roots were not observed. Root-induced pedotubules, or root bark casts filled with soil were



a. Worst case conditions. Friction angle = 28 degrees, cohesion = 0, seepage angle = slope angle (seepage parallels slope).



b. Average conditions. Friction angle = 31.6 degrees, cohesion = 0.084 kg cm-2, seepage angle = slope angle (seepage parallels slope).

Figure 5. Results of Infinite Slope Analyses. Note that observed RAR varied from 0.001 to 2.02 percent and averaged 0.17 percent.

D-030785

D-030785

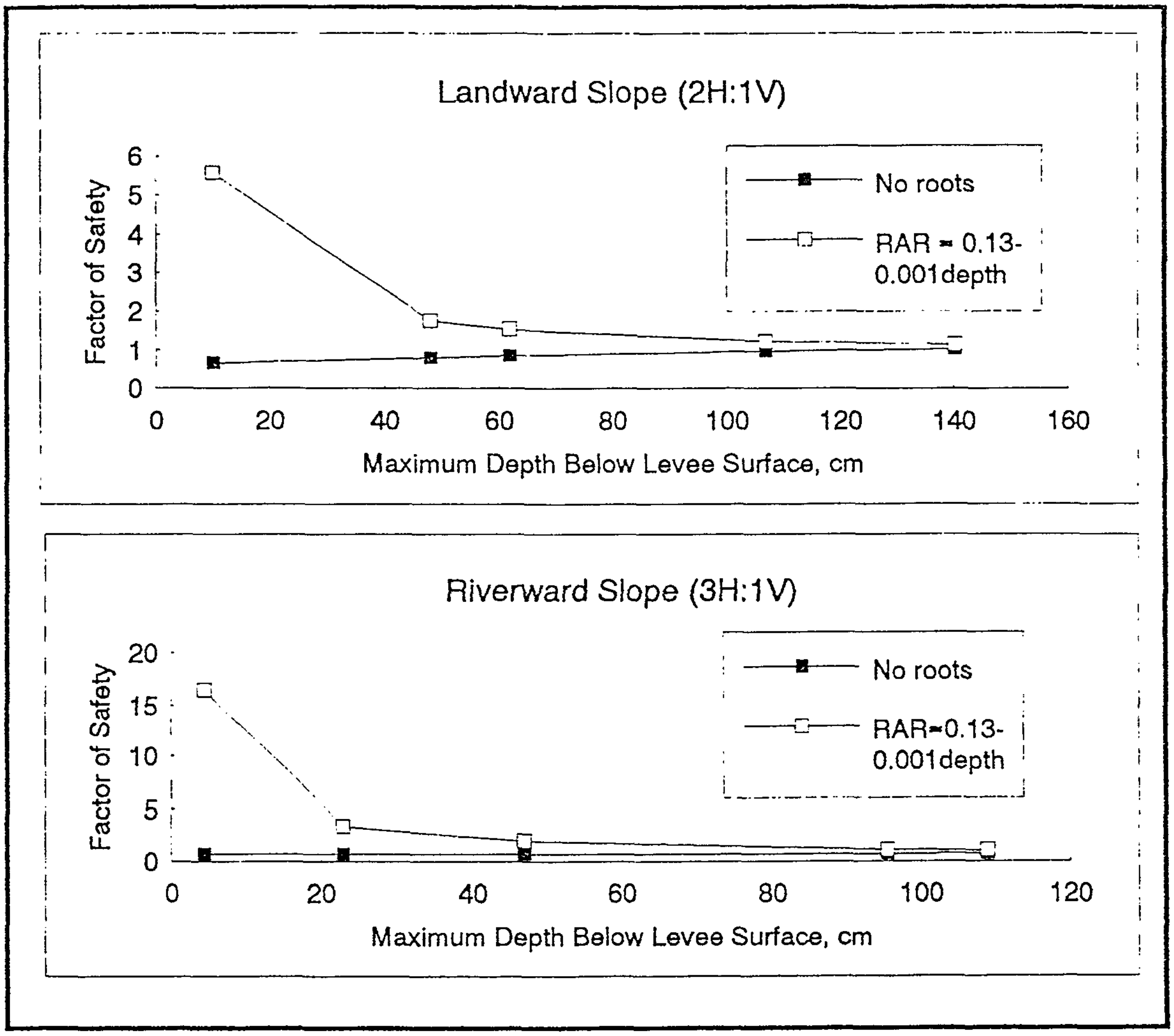


Figure 6. Effect of Roots on Safety Factor from Circular Arc Analysis.

common. The pattern of roots at the dead stump site suggests that the likelihood of roots penetrating this levee embankment is small. Nevertheless, it was not possible to quantitatively analyze the effects of a root-induced void on piping potential. The two-dimensional seepage analyses performed in this study cannot predict piping potential. A transient, three-dimensional analysis is necessary to obtain the point values of hydraulic head and exit seepage velocity that are required to determine whether seepage forces are high enough to promote internal erosion and propagate piping in the vicinity of a penetrating or partially penetrating seepage channel or macropore. We would expect the likelihood of pipe formation to be greater in less sandy, more cohesive soils. However, the chance of *root-induced* piping would be less for cohesive soils, since root penetration into the embankment would be limited to shallower depths (Davidson *et al.*, 1991).

Traditional practice of geotechnical engineering rarely considers biological factors. Our analyses indicate that biological factors (i.e., reinforcement by plant roots) have a significant, positive effect on the stability of the sandy levee we studied. Even low root concentrations sufficed to make the slope more secure under "worst case" scenarios (low shear strength, high water levels, etc.), because the small increases in soil shear strength that were caused by roots produced large increases in safety factor. Similar findings were reported by others for hillslopes (Greenway, 1987; Coppin and Richards, 1990).

What type of plant cover is best for slope stability? Our analyses indicated that beneficial effects on stability against shallow sloughing were greater for sites with highest average root density at shallow depth. The herbaceous site had the highest mean RAR for the top 30 cm of soil. However, if a single large root found at the herbaceous site (11.5 cm diameter) is excluded, mean RARs for the top 30 cm for herbaceous and woody dripline sites are similar. In contrast, workers studying plants growing on clay hillslopes reported that tree cover tended to have about twice as much root mass as herbaceous cover (Davidson *et al.*, 1991). Furthermore, our analysis did not consider species-based differences in root tensile strength. Davidson *et al.* (1991) reported that tensile strength of roots < 2 mm diameter was 1.5-8.5 times greater for woody than herbaceous species, and that among woody species, later successional species characteristically had stronger roots than early successional species. Woody species, which have larger roots at depth than herbaceous plants, are also more effective in preventing deeper seated sliding. Therefore, levee maintenance standards that permit woody shrubs and small trees would provide greatest environmental resource benefits and would enhance structural integrity without hazards associated with large trees such as wind-throwing. A variety of alternatives to the existing federal standard have been proposed (e.g., Carter and Anderson, 1981; Reclamation Board, 1988).

ACKNOWLEDGMENTS

Support for data collection and initial analysis was provided by the U.S. Army Corps of Engineers. Anne MacDonald planned and directed data collection and initial analysis. Imogene Blatz, Leslie Tacon, Wayne Sharp, Thomas Thomann, and Sterling Sorenson assisted with field data collection. Albert Edney, James Mock, James Battle, Thomas Thomann, Imogene Blatz, and Abu El-Shár assisted with data analysis. Anne MacDonald, D. J. Hagerty, E. H. Grissinger, R. F. Cullum, Pat Morris, and J. L. Miller reviewed a draft of this paper and provided many helpful comments. Trudy Olin assisted with retrieval of archived data. P. D. Mitchell prepared Figure 1.

LITERATURE CITED

Anonymous, 1992. Floodplain Management in the United States: An Assessment Report. Volume 1, Summary. Prepared for the Federal Interagency Floodplain Management Task Force by the Natural Hazards Research and Applications Information Center, University of Colorado, Boulder, Colorado.

ASTM, 1985. Standard Method for Particle-Size Analysis of Soils – ASTM D422. Annual Book of ASTM Standards. American Society for Testing Materials.

Bohm, W., 1979. Methods of Studying Root Systems. Springer-Verlag, New York, New York.

Carter, L. W. and G. L. Anderson, 1981. Riparian Vegetation on Flood Control Project Levees: Constraints and Opportunities. *In:* Proceedings: California Riparian Systems Conference, University of California-Davis, R. E. Warner and K. M. Hendrix (Editors). University of California Press, Berkeley, California, pp. 548-550.

Cedergren, H. R., 1967. Seepage, Drainage, and Flow Nets (First Edition). John Wiley and Sons, New York, New York.

Coppin, N. J. and I. G. Richards (Editors), 1990. Use of Vegetation in Civil Engineering. Butterworths, London.

Daar, S., W. Klitz, and W. Olkowski, 1984. The Role of Vegetation in an Integrated Pest Management Approach to Levee Management. *In:* Proceedings: California Riparian Systems Conference, University of California-Davis, R. E. Warner and K. M. Hendrix (Editors). University of California Press, Berkeley, California, pp. 551-555.

Davis, L. C., S. I. Ito, and P. T. Zwanck, 1967. Pilot Levee Maintenance Study. Bulletin No. 167, California Department of Water Resources, Sacramento, California.

Davidson, D. W., L. A. Kapustka, and R. G. Koch, 1991. The Role of Plant Root Distribution and Strength in Moderating Erosion of Red Clay in the Lake Superior Watershed. Transactions of the Wisconsin Academy of Sciences, Arts, and Letters 77:51-63.

Dennis, N. B., D. Ellis, J. R. Arnold, and D. L. Renshaw, 1981. Riparian Surrogates in the Sacramento/San Joaquin Delta and Their Habitat Values. *In:* Proceedings: California Riparian Systems Conference, University of California-Davis, R. E. Warner and K. M. Hendrix (Editors). University of California Press, Berkeley, California, pp. 566-576.

Fitzgerald, W. S. and R. E. Marsh, 1986. Potential of Vegetation Management for Ground Squirrel Control. Proceedings, Twelfth Vertebrate Pest Conference, University of California, Davis, California, pp. 102-107.

Gilbert, P. A. and S. P. Miller, 1991. A Study of Embankment Performance During Overtopping. Technical Report GL-91-23, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, 96 pp.

Gray, D. H. (Editor), 1991. Proceedings: Workshop on Biotechnical Stabilization. The University of Michigan, Ann Arbor, Michigan, 204 pp.

Gray, D. H. and T. Al-Refeái, 1986. Behavior of Fabric- Versus Fiber-Reinforced Sand. Journal of Geotechnical Engineering, American Society of Civil Engineers 112(GT8):804-820.

Gray, D. H. and A. T. Leiser, 1982. Biotechnical Slope Protection and Erosion Control. Van Nostrand Reinhold, New York, New York.

Gray, D. H., A. MacDonald, T. Thomann, I. Blatz, and F. D. Shields, Jr., 1991. The Effects of Vegetation on the Structural Integrity of Sandy Levees. Technical Report No. REMR-EI-5, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, 117 pp.

Gray, D. H. and H. Ohashi, 1983. Mechanics of Fiber Reinforcement in Sand. Journal of Geotechnical Engineering. American Society of Civil Engineers 109(3):335-353.

Greenway, D. R., 1987. Vegetation and Slope Stability. *In:* Slope Stability, M. G. Anderson and K. S. Richards (Editors). Wiley, Chichester, pp. 187-230.

Handy, R. L., 1986. Borehole Shear Test and Slope Stability. Proceedings: American Society of Civil Engineers, Geotechnical Specialty Conference, Blacksburg, Virginia, pp. 161-175.

Huang, Y. H., 1983. Stability Analysis of Earth Slopes. Van Nostrand Reinhold Company, New York, New York.

Huang, Y. H., 1986. Unsteady State Phreatic Surface in Earth Dams. Journal of Geotechnical Engineering 112(1):93-98.

Hynson, J. R., P. R. Adamus, J. O. Elmer, T. Dewan, and F. D. Shields, Jr., 1985. Environmental Features for Streamside Levee Projects. Technical Report E-85-7, Center for Natural Areas, South Gardiner, Maine, and U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Keller, E. A. and A. Brookes, 1984. Considerations of Meandering in Channelization Projects: Selected Observations and Judgments. Proceedings of the Conference River '83, pp. 384-397.

Maher, M. and D. H. Gray, 1990. Static Response of Sands Reinforced with Randomly Distributed Fibers. Journal of Geotechnical Engineering 116(11):1661-1677.

Nolan, M. H., 1981. Vegetation on Corps of Engineers Project Levees in the Sacramento-San Joaquin Valley, California. *In:* Proceedings: California Riparian Systems Conference, University of California-Davis, R. E. Warner and K. M. Hendrix (Editors). University of California Press, Berkeley, California.
Nunnally, N. R., F. D. Shields, Jr., and J. Hynson, 1987. Environmental Considerations for Levees and Floodwalls. Environmental Management 11(2):183-191.
Owings, D. H., M. Borchert, and R. Virginia, 1977. Correlates of Burrow Location in Beechey Ground Squirrels. Great Basin Naturalist 35:402-404.
Reclamation Board, 1988. Interim Guide for Vegetation on Flood Control Levees Under Reclamation Board Authority. Revised Draft No. 4, State of California, The Resources Agency, The Reclamation Board, Sacramento, California.
Reistenberg, M. H. and S. Sovonick-Dunford, 1983. The Role of Woody Vegetation on Stabilizing Slopes in the Cincinnati Area. Geological Society of America Bulletin 94:506-518.
Salmon, T. P., R. E. Marsh, and D. Stroud, 1987. Influence of Burrow Destruction on Recolonization by California Ground Squirrels. Wildlife Society Bulletin 15:564-568.
Sherard, J. L., 1986. Hydraulic Fracturing in Embankment Dams. Journal of Geotechnical Engineering, American Society of Civil Engineers 112(10):905-927.
Sidle, R. C., 1991. A Conceptual Model of Changes in Root Cohesion in Response to Vegetation Management. Journal of Environmental Quality 20(1):43-52.
Sims, P. L., and J. S. Singh, 1978. The Structure and Function of Ten Western North American Grasslands: II. Intra-Seasonal Dynamics in Primary Producer Compartments. Journal of Ecology 66(2):547-572.
Sims, P. L., J. S. Singh, and W. K. Laurenroth, 1978. The Structure and Function of Ten Western North American Grasslands: I. Abiotic and Vegetational Characteristics. Journal of Ecology 66(1):251-285.
Sullivan, B., 1992. Civil works Program Statistics. Fact Sheet, CECW-MP, Directorate of Civil Works, Headquarters, U.S. Army Corps of Engineers, Washington, D.C.
Tschantz, B. A. and J. D. Weaver, 1988. Tree Growth on Earthen Dams: A Survey of State Policy and Practice. Civil Engineering Department, University of Tennessee, Knoxville, Tennessee.
U.S. Army Corps of Engineers, 1968. Levee Maintenance Standards and Procedures. Engineer Manual 1130-2-335, Washington, D.C.
U.S. Army Corps of Engineers, 1978. Design and Construction of Levees. Engineer Manual 1110-2-1913, Washington, D.C.
VonGunten, M. W., 1984. SB-SLOPE: Slope Stability by the Simplified Bishop Method. Computer Software, VE/S, Inc., Fort Collins, Colorado.
Water and Engineering Technology, Inc., 1989. Geomorphic Analysis and Bank Protection Alternatives Report for Sacramento River (RM 78-178) and Feather River (RM 0-28), Draft Report, Contract No. DACW05-88-DO-0444, Delivery Order 5, U.S. Army Corps of Engineers, Sacramento, California.
Wineland, J. D., 1975. Borehole Shear Device. Proceedings: American Society of Civil Engineers-GT Specialty Conference (Volume 1), Raleigh, North Carolina, pp. 511-535.
Ziemer, R., 1981. Roots and Shallow Stability of Forested Slopes. *In:* Erosion and Sediment Transport in Pacific Rim Steeplands. Publications No. 132, International Association of Hydrologic Sciences, Christchurch, New Zealand, pp. 343-361.

D-030788