Role of vegetation in levee slope stability and revetment durability

F. Douglas Shields, Jr.

USDA ARS National Sedimentation Laboratory
Scope of talk

- Sacramento River levee study (Corps, 1980s)
- Simulation of effects of vegetation on levee slope stability using ARS bank stability model
- Sacramento River revetment study (Corps, 1980s)
- Acknowledgments
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- **Field data**
  - Summer, 1987
  - 10-km-long reach on west bank of Sacramento River upstream from I-5 bridge.
- Effect of vegetation on riverside levee embankment slopes
- Focus was on 6 sites with varying types of vegetative cover
  - All herbaceous
  - Dead stump
  - Valley oaks (2, 0.7 m diam)
  - Willows
  - Elderberry shrubs
  - Black locust
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- Field data collection
  - L-shaped trenches were excavated at each site. Trenches were 1.2 m deep.
  - Trenches ran parallel and perpendicular to levee crest
  - Trenches coincided with driplines of trees
  - At the elderberry site, the perpendicular trench went through the center of a clump of bushes.
Perpendicular trench, valley oak site
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- Field data--Physical
  - Cross section surveys
  - Soil properties
    - Density
    - Grain size
    - Permeability
    - Shear strength
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Results--Physical

- Levees were 4 m high with crest widths of 6 m. Side slopes 2H:1V (land), >3H:1V (river)
- Soils were medium to fine sands (SP)
- $D_{50}$ 0.2 to 0.4 mm
- Dry densities 1360 to 1470 kg m$^{-3}$
- Permeability 0.03 to 0.07 cm sec$^{-1}$
- Friction angle 31.6 $\pm$ 3.7 deg
- Cohesion only 8.2 $\pm$ 4.2 kPa
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- Field data—Botanical
  - Above ground
  - Below ground
    - Trench walls carefully excavated
    - Root locations and sizes mapped on acetate overlay
    - Also voids, macropores, mineral inclusions, stratigraphic features
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- Field data--Botanical
- Below ground
  - Root maps used to compute “root area ratios” or \( \text{RAR} = \frac{\Sigma A_r}{A_t} \)
  - RAR computed by 10-cm depth increments
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Results—Botanical

- Above ground (Oct thru May)
  - Entire reach riverward slope cover was 11% trees, 0.1% shrubs, 40.4% ground cover
  - Trench sites were 0-72% trees, 0-33% shrubs, 0-24% ground cover

- Below ground
  - RAR’s varied from 0.001% to 2.02%, mean = 0.17% ± 0.30%
  - Root numbers declined exponentially with size
  - Root frequency and RAR declined with depth.
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Mean Root Area Ratios

No significant difference in mean RAR at depths > 20 cm
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Vertical distributions of roots

Biome curves from Jackson et al. 1996
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- Qualitative visual observations
- Analyses
  - Seepage
    - 2-d, finite difference flow net, 0.3-m mesh
    - Riverside water surface at 90% of levee height, landside at levee toe
    - Vegetation effects simulated by changing (± order of magnitude) permeability of 0.3-m-thick surface layer.
  - Slope stability
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**Results—qualitative observations**

- Density of voids > 5 mm ranged from 0 to 10 m$^{-2}$ and averaged 1.65 m$^{-2}$
- Lateral roots at dead oak stump angled downward
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- Qualitative visual observations
- Analyses
  - Seepage
  - Slope stability
    - Infinite slope
    - Circular arc

Assumed steady state hydraulic loading
Sacramento River levee study

**Results**

- Seepage analyses
  - Increasing surface permeability had little effect on seepage
  - A surface layer 10 times less permeable than the core elevated the phreatic surface and increased the discharge area on the landward slope.

- Stability analyses
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- Qualitative visual observations
- Analyses
  - Seepage
  - Slope stability
    - Infinite slope
    - Circular arc—simplified Bishop method of slices
    - Vegetation effects simulated by increasing soil cohesion
      - $C_R$ (in kg cm$^{-2}$) = 0.23 x RAR
      - This increases cohesion by about 50% for our mean RAR and mean soil cohesion
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Infinite slope stability analysis results

2H:1V slope (landward)
Friction angle = 28 deg
Cohesion = 0
Seepage angle = slope angle
RAR not varied with depth

Depth to failure surface

Fs increases from 0.6 to 8.8 with increasing RAR from 0.01 to 1

H = 10 cm
H = 20 cm
H = 40 cm
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Circular arc stability analysis results

3H:1V slope (riverward)
Friction angle = 30 deg
Cohesion = 0
Sudden drawdown
RAR a weak linear function of depth

RAR = 0.13 - 0.001Z

Fs < 1 for no roots
Fs ranges from 16.5 to 1.1 for rooted case
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Mean Root Area Ratios

Linear fit used for circular arc slope stability analyses….based on elderberry parallel trench
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- **Key findings**
  - Roots concentrated near surface
  - Large lateral roots from stump angled downward
  - Vegetation made an important contribution to slope stability
  - Roots did not create voids
  - Voids were associated with animal activity

- **Implications**
  - Maintenance standards should favor woody shrubs and small trees

- **Limitations**
  - No quantitative analysis of piping
  - No analysis of windthrow issues
Vegetation effects on slope stability

- **ARS bank stability model**—key characteristics
  - Intended to model streambanks
  - Simulates wedge-type slope failure
  - Static conditions, 2-d geometry
  - Horizontal phreatic surface
  - Simulates vegetation by increasing soil cohesion
Recent advances (Pollen 2007):

- Vegetation is modeled using a “fiber bundle” approach, which is more realistic than previous constructs that assumed all roots break simultaneously.
- Root contributions to soil strength varied based on vegetation, and soil type, and moisture content.
- RipRoot algorithm

http://www.ars.usda.gov/Research/docs.htm?docid=5044
Vegetation effects on slope stability

- 4m high sand/silt levee
- Soil cohesion = 0.84 kPa
- 2H:1V and 3H:1V slopes
- Most critical failure surface angle selected for each profile modeled
- Phreatic surface is horizontal and at 80% of levee height
Vegetation effects on slope stability

Vegetation treatments modeled:

- Bunch grass (0.5m deep roots): 15 kPa
- Young trees (1.0m deep roots): 3 kPa
- Mature trees (1.0m deep roots): 20 kPa

Vegetation planting locations:

- Top of levee
- Riverward side slope of levee
- Top and side of levee

Hydrologic conditions modeled:

- Low flow, low watertable
- High flow, high watertable
- Low flow, high watertable
Also commonly called tussock grass, bunch grasses are any grass that grows in clumps or tufts, rather than forming a sod or mat, and does not spread by stolons or rhizomes. As perennial plants, they live more than one season. With long roots that may reach two meters into the soil, bunch grasses can find water where other plants wither.

Bunch grasses occur in almost any habitat where grasses are found, from deserts, swamplands, savannas, forests and tundra.

DOUG SHIELDS, 7/17/2007

"low" = 20% of levee height
"high" = 80% of levee height

DOUG SHIELDS, 7/19/2007
Vegetation effects on slope stability

Results—worst case hydrologic conditions

Factors of Safety

Levee is unstable without root reinforcement ($F_s = 0.54$)
Vegetation effects on slope stability

- **Key findings**
  - Under worst case assumptions, riverside slope is unstable without vegetation
  - For Fs, mature trees > bunch grass > young trees

- **Implications**
  - Maintenance standards should favor bunch grass or trees

- **Limitations**
  - Only analyzed wedge-type slope failure
  - Effect of vegetation on soil permeability and thus seepage not considered
  - Windthrow hazard not considered
  - Piping potential not considered
Sacramento River revetment study

- Revetments are a key component of the Sacramento River Flood Control Project
- Revetments sometimes coincide with levee slopes
- Revetments are often colonized by volunteer vegetation, especially woody species
- Revetment vegetation has also been somewhat controversial
Sacramento River revetment study

- This investigation differs from the previous two in that it is purely empirical.
- Historical records, air photos, and field inspections were used to assess the condition of Sacramento River revetments before and after a large event.
- Damage rates for vegetated and unvegetated revetments, allowing for type of stone, construction date, and bank curvature were computed and compared using Chi-squared statistics.
Sacramento River revetment study

- Study reach
  - RM 84.5 to RM 119
  - between Fremont and Tisdale Weirs
  - no major inflows or outflows in this reach
The event

- February 1986 flood
- $Q_{\text{peak}} = 925 \text{ m}^3\text{ s}^{-1}$
- Mean velocity $\sim 1.3 \text{ m s}^{-1}$
Sacramento River revetment study

- Data--mapping
  - DWR Inspection records, Fall 1985 and Spring 1986
  - Aerial photos 1984-85 and 1986-1987
  - Requests from local interests to the Corps under PL84-99 for assistance with revetment repair confirmed by contacting local interests
  - Visual inspection by boat, Sept 1989

- Variables recorded
  - Revetment condition
  - Construction material
  - Vegetation

- Information was compiled on a series of overlays for base maps made from 1987 photomosaics showing revetment locations and construction dates.
Sacramento River revetment study

- Database
- Revetments were divided into 30-m-long segments
- For each segment, a data record was created containing:
  - Spatial location
  - Bank curvature
  - Construction date
  - Revetment material
  - Preflood vegetation (inspection records)
  - Postflood vegetation (inspection records)
  - Preflood vegetation (aerial photos)
  - Postflood vegetation (aerial photos)
  - Revetment condition (damaged or not)
Sacramento River revetment study

- **Vegetation types**
  - 1—bare rock or soil or herbaceous growth < 4 ft high
  - 2—woody vegetation 4-12 ft high
  - 3—woody vegetation > 12 ft high

Classification based on the largest *individual* plants growing on each segment
Results

- About two-thirds of bankline was revetted
- About 10% of the revetted bankline supported some type of woody vegetation
- State inspection records under-reported revetment vegetation by 80% relative to aerial photos
- Only five revetment sites were reported as damaged during 1986 flood in PL 84-99 request files
- We classified about 3% of revetted bankline as damaged in Sept 1989 visual inspection
- Local scour downstream of tree trunks was not observed
Sacramento river revetment study

- Damage rates based only on:
  - Vegetation
    - Unvegetated = 2.8%, vegetated = 4.7% (p = 0.11)
  - Bank curvature
    - Straight = 3.7%, curved = 2.8% (p = 0.35)
  - Material
    - Cobble = 3.0%, riprap = 2.8% (p = 0.83)
  - Date of construction
    - Pre-1950 = 7.9%, post-1950 = 2.5% (p = 0.0002)
Sacramento River revetment study

Results—Damage rates in percent

Damage rates higher for unveg 6 categories to 3

60% = 3/5
Sacramento River revetment study
Results—Damage rates in percent

RIPRAP REVETMENTS

Damage rates higher for unveg 3 categories to 1?
2 ties with both = 0

Unvegetated
Vegetated
Sacramento River revetment study

- **Key findings**
  - Damage rates for revetments supporting woody vegetation tended to be lower than for unvegetated revetments of the same age located on banks of similar curvature.
  - Chi-squared tests indicated damage rates were greater for pre-1950 revetments, but were unable to detect differences based on vegetation.

- **Implications**
  - During conditions that prevailed in February 1986, revetment durability was not adversely impacted by volunteer woody vegetation

- **Limitations**
  - Empirical study
  - Low damage rates
  - No assessment of vegetation impacts on flood fight, conveyance or inspection
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