Interactions between Riparian Vegetation and Levee and Bank Stability

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Stability is decreased by...

Soil moisture

Positive pore-water pressure

Hydraulic erosion
Stability is increased by....

Evapo-transpiration and root reinforcement

Drainage- develop matric suction

Toe protection
Let’s Dispels Some Myths

1. Studies of streambank processes and the role of vegetation do not apply to levees (Define the processes!!);
2. There is no or limited data on the tensile strength of roots by species;
3. Root distributions and typology of roots are not documented;
4. Geotechnical data is assumed;
5. Root reinforcement and stability cannot be modeled.

Still, it is a complex issue and there is much more to be learned
Root Reinforcement Modeling


Applied Studies


Banks versus Levees: The Processes

- Hydrologic Processes
  - Vertical infiltration (precipitation)
  - Lateral infiltration (streamflow)
  - Evaporation (soil-air interface)
  - Transpiration (vegetation)
Banks versus Levees: The Processes

- **Hydraulic Processes**
  - Fluid shear (streamflow)
  - Lateral seepage (streamward)
  - Piping
  - Roughness (fluid drag)
  - Fluid shear (streamflow)
  - Lateral seepage (streamward)
  - Lateral seepage (landward)
  - Piping
  - Roughness (fluid drag)
Banks versus Levees: The Processes

- Geotechnical Processes
  - Shear strength (soil)
  - Positive pore-water pressure
  - Matric suction
  - Root reinforcement
  - Surcharge
  - Windthrow
Vegetation...Streambank Considerations

- Above and below-ground biomass
- Process Domains
- “Engineers” in channel adjustment

<table>
<thead>
<tr>
<th>Process Domain</th>
<th>Geotechnical</th>
<th>Hydrologic</th>
<th>Hydraulic</th>
</tr>
</thead>
</table>
| Above Ground   | • Surcharge  | • Interception  
|                |              | • Evapo-transpiration | • Increased roughness  
|                |              |                      | • Reduced applied shear stress |
| Below Ground   | • Root reinforcement  
|                |              | • Increased infiltration  
|                |              | • Increased matric suction | • Increased critical shear stress |
Forces Affecting Soil Shear Strength

- **Cohesion**: electro-chemical bonds between particles
- **Friction**: inter-particle roughness
- **Pore-water pressure**: reduces effective friction
- **Matric suction**: apparent cohesion
- **Normal load**: weight of bank increases friction

Shear surface
Factor of Safety Equation for Planar Failures

\[ F_s = \frac{\Sigma c'_i L_i + (S_i \tan \phi^b_i) + \left( W_i \cos \beta - U_i + P_i \cos (\alpha - \beta) \right) \tan \phi'_i}{\Sigma W_i \sin \beta - P_i \sin (\alpha - \beta)} \]

- \( c' \) = effective cohesion;
- \( L \) = length of failure plane;
- \( S \) = force produced by matric suction on the unsaturated part of the failure surface;
- \( \phi^b \) = rate of increasing shear strength with increasing matric suction;
- \( W \) = weight of failure block;
- \( \beta \) = failure-plane angle;
- \( U \) = hydrostatic-uplift force due to positive pore-water pressures on the saturated part of the failure plane;
- \( P \) = hydrostatic-confining force provided by the water in the channel; and
- \( \phi' \) = angle of internal friction (rate of increasing shear strength with increasing normal force).

Simon et al., 2000
## Hydraulic and Geotechnical Effects

### Hydraulic Processes

- Reduces the available boundary shear stress (roughness), and increases the shear resistance to particle detachment (reinforcement).

### Geotechnical Processes

- Increases shear strength and resistance to failure by gravity (reinforcement, transpiration).
## Effects of Vegetation on Stability

<table>
<thead>
<tr>
<th></th>
<th>Mechanical</th>
<th>Hydrologic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stabilizing Effects</strong></td>
<td>Increased strength due to roots</td>
<td>Canopy interception</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transpiration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Destabilizing Effects</strong></td>
<td>Surcharge Windthrow</td>
<td>Increased infiltration rate and capacity</td>
</tr>
</tbody>
</table>

**Problem**: how much effect (+ and -) do these combined factors have on bank stability?
Geotechnical Processes: Force vs. Resistance

What Role Does Vegetation Play?

Factor of Safety \((F_s)\) = \(\frac{\text{Resisting Forces}}{\text{Driving Forces}}\)

If \(F_s\) is greater than 1, bank is stable. If \(F_s\) is less than 1 bank will fail. (We usually add a safety margin: \(F_s > 1.3\) is stable.)

**Resisting Forces**
- soil shear strength
- matric suction
- root reinforcement
- confining force

**Driving Forces (gravity)**
- bank angle
- weight of soil mass
- weight of water in bank
- bank height
- surcharge
Quantifying the Hydrologic Effects of Vegetation

**Beneficial Effects:** Increase in strength due to matric suction and reduced pore-water pressure

- Rainfall Interception
- Transpiration

**Detrimental Effects:**
- Enhanced infiltration
- Enhanced permeability
Monitoring the Hydrologic Effects of Vegetation

- Rainfall, stemflow and throughfall monitored spatially and in real-time
- Pore-water pressure below plots monitored using tensiometers
Canopy Interception - Seasonal

Winter throughfall = 0.96x + 0.32
\[ R^2 = 0.99 \]

Summer throughfall = 1.00x - 0.98
\[ R^2 = 0.97 \]
Matric Suction: Negative Pore-water Pressure

Suction is negative pore water pressure

\[ \mu = -\gamma_w h_w \]

\[ \mu = \gamma_w h_w \]

depth

pressure

matric suction: \[ \psi = u_a - u_w \]

Where \( u_a \) is the air pressure
\( u_w \) is the pore water pressure
Therefore a negative value of pore water pressure is a positive suction
Incorporating Matric Suction as Apparent (total) Cohesion

\[ c_a = c' + (\mu_a - \mu_w) \tan \phi^b \]

Where:

- \( c_a \) = apparent (total) cohesion
- \( c' \) = effective cohesion
- \( (\mu_a - \mu_w) \) = suction on the failure plane
- \( \phi^b \) = angle representing the relation between the shear strength and the matric suction
Hydrologic Effects: 
*Infiltration and Matric Suction*

- 30 cm
- 100 cm
Hydrologic Effects:

Infiltration and Matric Suction

MATRIC SUCTION, IN KPA

RAINFALL, IN MM

200 cm

270 cm
Hydrology Findings: Example

• 2% of rain is intercepted by riparian strip canopy (high intensity events, low canopy cover during winter/spring)
• Trees increase infiltration capacity, concentrating more water in upper 30-100 cm soil than on bare or grass-covered banks
• Trees maintain suction at depth (200-300 cm) into spring
Hydrologic Effects:
Evapo-transpiration and Matric Suction

Tensiometers installed at 0.3 m and 0.7 m depths below soil surface.
• Changes in apparent cohesion due to matric suction varied from **-1.0 to 3.2 kPa** at 30 cm and **-0.5 to 5.0 kPa** at 70 cm, when compared to the control case.

• The hydrological reinforcing effect was greatest during the **summer** and **autumn** when ET was highest.

• In summer, increased apparent cohesion from saplings (<3 yrs old) by ET, were comparable to **mechanical root-reinforcement** for **5 to 12 year-old** riparian tree species.

**Example: Hydrologic Effects**

*Evapo-transpiration and Matric Suction*
Effects of Vegetation on Hydraulics

- Alter boundary layers (may create two-layer system) and velocity distribution (blunt profile in vegetation zone)
- Turbulence may be dominated by vegetation-induced rather than boundary-induced
- Create coherent flow structures
- Increase flow resistance and trap sediment
Vegetation and Fluid Drag

- Vegetation is an additional component of drag

$$f_d = \frac{1}{2} C_D \rho A |\overline{U}_v| U_v = C_D \rho \alpha_v \frac{2c}{\pi D_e} |\overline{U}_v| U_v$$

- $C_D$ drag coefficient, $c$ is vegetation density, and $\alpha_v$ is vegetation shape factor

- Determination of $C_D$ is not trivial
  - Bulk vs. individual
  - Effects of submergence and orientation
Vegetation Effects on Velocity and Turbulence

a) Terrestrial Canopy: Unconfined
\[ \frac{H}{h} \to \infty: \quad \rho \bar{u} \bar{w} \approx \frac{\partial P}{\partial x} \]

b) Depth-Limited, Submerged Canopy
\[ \frac{H}{h} = 2: \quad \rho \bar{u} \bar{w} \approx \frac{\partial P}{\partial x} \]

\[ S = \frac{\partial H}{\partial x} \]

Emergent Canopy
\[ \frac{H}{h} = 1, \quad \text{Emergent:} \quad \rho \bar{u} \bar{w} \ll \frac{\partial P}{\partial x} \]

wake turbulence, \( L_w \sim d_p \)

(Nepf and Vivoni, 2000)
Grain Roughness and Effective Stress Acting on Surfaces

\[ \tau_{\text{eff}} = \tau_o \left( \frac{n_g^2}{n^2} \right) \]

\( \tau_{\text{eff}} \) = effective shear stress acting on grain, in Pa

\( \tau_o \) = boundary shear stress, in Pa

\( n_g \) = roughness due to grains, in Pa (0.0156 for fines)

\( n \) = Manning’s roughness coefficient

For \( n \) of 0.035 (fairly typical with some vegetation), this results in an effective grain stress of about 20% of the non-vegetated case!!
In bend: $\tau_o = 75.3$ Pa; Eroded area = 0.964 m$^2$
Shear Stress in Bend Coupled with Reduced Stress from Vegetative Effects

In bend (total stress):
\[ \tau_o = 75.3 \text{ Pa}; \text{ Eroded area} = 0.964 \text{ m}^2 \]

In bend: (effective stress):
\[ \tau_o = 15.0 \text{ Pa}; \text{ Eroded area} = 0.155 \text{ m}^2 \]
Hydraulic Effects: Critical Shear Stress

Jet Tests in Root-Permeated Soils

\[ y = 0.44 \times^{-0.77} \]

\[ R^2 = 0.75 \]
## Hydraulic Effects: Critical Shear Stress

<table>
<thead>
<tr>
<th>Site</th>
<th>Condition</th>
<th>Average $\tau_c$ (Pa)</th>
<th>Average $k$ (cm$^3$/N·s)</th>
<th>Median $\tau_c$ (Pa)</th>
<th>Median $k$ (cm$^3$/N·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTR3</td>
<td>Rooted</td>
<td>32.3</td>
<td>5.0</td>
<td>23.4</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td>Non-rooted</td>
<td>6.80</td>
<td>1.35</td>
<td>8.12</td>
<td>1.35</td>
</tr>
<tr>
<td>Trout 9</td>
<td>Rooted</td>
<td>43.2</td>
<td>3.05</td>
<td>43.2</td>
<td>3.72</td>
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<tr>
<td></td>
<td>Non-rooted</td>
<td>1.68</td>
<td>13.6</td>
<td>1.68</td>
<td>13.6</td>
</tr>
<tr>
<td>Trout 4</td>
<td>Rooted</td>
<td>31.1</td>
<td>5.3</td>
<td>33.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Non-rooted</td>
<td>1.95</td>
<td>36.2</td>
<td>1.12</td>
<td>40.6</td>
</tr>
</tbody>
</table>
Root Tensile Strength

Predict increase in cohesion from root tensile strength testing and root-area ratio (after Wu et. al. 1979)

\[ c_r = T_r \left( \frac{A_r}{A_w} \right) (\cos \theta \tan \phi + \sin \theta) \]

- \( c_r \) = cohesion due to roots kPa
- \( T_r \) = root tensile strength kPa
- \( A_r \) = area of roots m\(^2\)
- \( A_w \) = area of shear surface m\(^2\)
- \( \theta \) = orientation of roots degrees
- \( \phi \) = soil friction angle degrees

\[ (\cos \theta \tan \phi + \sin \theta) \approx 1.2 \]
Methodology: Testing root tensile strengths

- Load cell
- Displacement transducer

Graph showing:
- Method: Testing root tensile strengths
- Time, in minutes: 1605.40, 1605.45, 1605.50, 1605.55, 1605.60, 1605.65, 1605.70
- Tensile strength, in megapascals
- Displacement, in centimeters
- Root diameter at rupture = 0.75 cm

Legend:
- Load cell
- Displacement transducer

Graph details:
- MD 2.12: square in first 100,000 lb
- Imposed load
- Imposed displacement

Time range: 10.02 - 10.07
Root-Strength: Species Comparison

![Graph showing the comparison of root strength among various species.](image-url)
(Willow mean age=5, n=16, Sweetgum age=10, n=15, River birch age=7, n=11, Sycamore age=7, n=12)
Number of Roots and Depth: Grasses

(Gamma grass mean age=5, n=3)  (Switch grass mean age=5, n=3)

Gamma Grass

Switch Grass
Geotechnical: Root Reinforcement

Bank cover (1m high vertical bank or levee, silt, saturated)
Assumptions of Wu et al.’s (1979) Equation

- All the roots are aligned perpendicular to the shear plane
- Full tensile strength of all the roots is mobilized at the time the soil fails
- All the roots are well anchored and do not simply pull out of the soil when tensioned
RipRoot Model Development

Simple rules and assumptions using Fiber Bundle Model (*progressive breaking*)

- An initial load is distributed evenly between the $n$ roots.
- This load is increased until one of the roots breaks.
- The load that was carried by the broken root is redistributed *equally* to the remaining ($n-1$) intact roots.
## Root Reinforcement Estimates

<table>
<thead>
<tr>
<th>Species</th>
<th>Number of roots</th>
<th>RipRoot estimate (kPa)</th>
<th>Wu equation estimate (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cottonwood</td>
<td>200</td>
<td>2.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Black willow</td>
<td>200</td>
<td>4.7</td>
<td>13.2</td>
</tr>
<tr>
<td>River birch</td>
<td>200</td>
<td>5.8</td>
<td>18.9</td>
</tr>
</tbody>
</table>
Validation of root reinforcement estimates

- Direct-shear tests with and without roots
- 10 control samples
- 30 samples with roots – number and diameters of roots crossing the shear plane recorded
- Root reinforcement calculated by subtracting the mean control value from each sample with roots
RipRoot: Validation

Wu equation over-estimates root reinforcement by 600 to 1000 %

Pollen and Simon 2005 Water Resources Research
- 2-D wedge- and cantilever-failures
- Tension cracks
- Search routine for failures
- Hydraulic toe erosion
- Increased shear in meanders
- Accounts for grain roughness
- Complex bank geometries
- Positive and negative pore-water pressures
- Confining pressure from flow
- Layers of different strength
- Vegetation effects: RipRoot
- Inputs: $\gamma_s$, $c'$, $\phi^b$, $h$, $u_w$, $k$, $\tau_c$
Root Reinforcement using RipRoot

Simulate the mechanical effects of *bank top* vegetation on bank stability using a root-reinforcement model

RipRoot (Pollonen and Simon, 2005) is a global load-sharing fiber-bundle model. It explicitly simulates both the snapping of roots and the slippage of roots through the soil matrix, by determining the minimum applied load required to either break each root or pull each root out of the soil matrix. As the strength of each root is removed from the fiber bundle, the load is redistributed to the remaining roots according to the ratio of the diameter of each root to the sum of the diameters of all the intact roots. RipRoot builds on earlier work by Waldron (1977), Wu et al. (1978) and Waldron and Dakessian (1981).

Run Root-Reinforcement Model

Root-Reinforcement Model Output

List of Species
Percent of Assemblage

Added cohesion due to roots, $c$, 

For the case: Wet meadow vegetation
Simulate the mechanical effects of bank top vegetation on bank stability using a root-reinforcement model

RipRoot (Pollen and Simons, 2005) is a global-scale, fiber-bundle model that explicitly simulates the snapping of roots and the slipping of roots through the soil matrix, determining the maximum applied load required to either break each root or pull each root out of the soil matrix. As the strength of each root is removed from the fiber bundle, the load is redistributed to the remaining roots according to the ratio of the diameter of each root to the sum of the diameters of all the intact roots. RipRoot builds on earlier work by Waldron (1977), Wu et al. (1979) and Waldron and Delissian (1981).

Run Root-Reinforcement Model

List of Species: Wet Meadow
Percent of Assemblage: 100;
Added cohesion due to roots, $c_r$: 4.3 kPa

Output

Additional cohesion according to RipRoot = 4.36
Additional cohesion according to Wu et al. (1979) = 9.4

Root-Reinforcement Model Output

List of Species: Wet Meadow
Percent of Assemblage: 100;
Added cohesion due to roots, $c_r$: 4.3 kPa

References and Data Sources:
DOI: 10.1029/2004WR003801.

Data Sources:
Austin DN, Thoms M. 1994. BMW engine vegetation program. 12(4), 6-16.

Unit Converter
Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

- Layer 1: Rounded sand, Silt, Stiff clay, Soft clay, Own data
- Layer 2: Rounded sand, Silt, Stiff clay, Soft clay, Own data
- Layer 3: Rounded sand, Silt, Stiff clay, Soft clay, Own data
- Layer 4: Gravel, Angular sand, Rounded sand, Silt, Stiff clay
- Layer 5: None

Vegetation safety margin: 50
Reach Length: 100 (m)
Constituent concentration (kg/kg): 0.001

Water table depth (m) below bank top:
- Layer 1: -6.79 kPa
- Layer 2: -12.26 kPa
- Layer 3: -12.71 kPa
- Layer 4: 0.74 kPa
- Layer 5: 10.30 kPa

Water table depth (m):
- 2.00

Pore Pressure From Water Table:
- Layer 1: -12.26 kPa
- Layer 2: 0.74 kPa
- Layer 3: 10.30 kPa
- Layer 4: 16.68 kPa
- Layer 5: 24.03 kPa

Factor of Safety: 2.10

Use in Design: 1:1 (Design) Geometry Stable...However

Graph showing bank profile, base of layers, failure plane, water surface, and water table.
Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Gravel</td>
</tr>
<tr>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Angular sand</td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Rounded sand</td>
</tr>
<tr>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Soft clay</td>
</tr>
<tr>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
</tr>
</tbody>
</table>

Vegetation safety margin: 50

Reach Length: 100 m

Constituent concentration (kg/kg): 0.001

Water table depth (m) below bank top

<table>
<thead>
<tr>
<th>Water table depth (m) below bank top</th>
<th>Use water table</th>
<th>Input own pore pressures (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>

Own Pore Pressures

<table>
<thead>
<tr>
<th>Own Pore Pressures</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
<td>2.45</td>
<td>15.45</td>
<td>25.02</td>
<td>31.39</td>
<td>38.75</td>
</tr>
</tbody>
</table>

Pore Pressure From Water Table

<table>
<thead>
<tr>
<th>Pore Pressure From Water Table</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
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<tbody>
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<td>15.45</td>
<td>25.02</td>
<td>31.39</td>
<td>38.75</td>
</tr>
</tbody>
</table>

Factor of Safety: 0.67

Unstable

1:1 Geometry **Unstable** with Raised Water Table
Still **Unstable** with Black Willow

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round</td>
<td>Round</td>
<td>Round</td>
<td>Round</td>
<td>Gravel</td>
</tr>
<tr>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Sand</td>
</tr>
<tr>
<td>Soft</td>
<td>Soft</td>
<td>Soft</td>
<td>Soft</td>
<td>Clay</td>
</tr>
<tr>
<td>clay</td>
<td>clay</td>
<td>clay</td>
<td>clay</td>
<td>own data</td>
</tr>
</tbody>
</table>

**Vegetation safety margin (age)**
- Willow - black (5 yrs)
- 50

**Vegetation safety margin concentration (kg/kg)**
- 0.001

**Water table depth (m) below bank top**
- Own data
- -6.79
- -12.71
- -12.71
- 1.56
- 3.52

**Reach Length (m)**
- 100

**Constituent concentration (kg/kg)**
- 0.001

**Factor of Safety**
- 0.81
- Unstable
Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
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</thead>
<tbody>
<tr>
<td>Rounded sand</td>
<td>Silt</td>
<td>Stiff clay</td>
<td>Soft clay</td>
<td>Own data</td>
</tr>
<tr>
<td>Silt</td>
<td>Stiff clay</td>
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<tr>
<td>Soft clay</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
</tr>
</tbody>
</table>

**Vegetation safety margin concentration (kg/kg)**
- 50

**Water table depth (m) below bank top**
- 0.5

**Pore Pressure (kPa)**
- From Water Table
- Layer 1: -6.79
- Layer 2: -12.71
- Layer 3: -12.71
- Layer 4: 1.56
- Layer 5: 3.52

**Pore Pressure From Water Table**
- Layer 1: 2.45
- Layer 2: 15.45
- Layer 3: 25.02
- Layer 4: 31.39
- Layer 5: 38.75

**Factor of Safety**
- 1.28

**Conditionally stable**

**Bank top vegetation cover (age)**
- River birch (7 yrs)

**Vegetation safety margin**
- 50

**Reach Length (m)**
- 100

**Constituent concentration (kg/kg)**
- 0.001

**Stable with River Birch or Sycamore**

**bank profile**

**base of layer 1**

**base of layer 2**

**base of layer 3**

**base of layer 4**

**failure plane**

**water surface**

**water table**
Effects of Different Species by Age

3m-high silt bank or levee, under drawdown conditions, with root-reinforcement (Pollen-Bankhead and Simon, 2009, Earth Surface Processes and Landforms)

$F_s = 1.30$ conditionally stable
Combined Effects

Factor of Safety

Rainfall
Control (bare bank)
Mixed tree cover
Gamma grass cover

Failure Threshold
Hydrologic and Mechanical Effects

Mechanical effects
Hydrologic effects
Control (bare soil)

March 2000 bank failure
February 2001 bank failure
Conclusions

- Interactions between vegetation and levee stability are complex and involve multiple processes/mechanisms that vary spatially and temporally.

- Hydrological effects of vegetation can be considerable, producing by far the greatest reinforcing effect to the soil BUT, values vary throughout the year and may not be at a maximum when stability is most critical.

- Root reinforcement is more constant throughout the year. Roots can provide stability at times of year when $F_S$ is most critical.

- Can be quantified with RipRoot and BSTEM