Culvert Design Process

1. Hydrology
2. Site Assessment
3. Alignment and Profile
4. Bed and Banks
5. Structure
6. Sediment Mobility & Stability
The big questions:

• Is the mobility of sediment in the design channel similar to the reference reach?

• Is sediment transport maintained through the structure during low/moderate floods?

• Are key pieces and grade controls stable?
Presentation outline

Background
• Bedload transport
• Channel types and bed mobility/stability

Why do bed stability-mobility analysis?

Flow hydraulics and sediment entrainment

Design application
• Bed mobility
• Bed stability
Bedload transport phases

Phase I bedload transport:
The transport of fine sediment over the immobile armor layer

Phase II bedload transport:
The armor layer is breached and the bed is mobilized
Surface armor layer
<table>
<thead>
<tr>
<th>Channel – Bed Type</th>
<th>Relative Mobility</th>
<th>Typical Transport at Bankfull</th>
<th>Structure</th>
<th>Channel Type</th>
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</thead>
<tbody>
<tr>
<td>Boulder Cobble</td>
<td>Low</td>
<td>Phase I</td>
<td>Steps</td>
<td>Rosgen A</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Cascade Step Pool</td>
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<tr>
<td>Cobble Gravel</td>
<td>High</td>
<td>Phase I Phase II</td>
<td>Particle clusters Armor</td>
<td>Rosgen B C Plane Bed Pool Riffle</td>
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<tr>
<td>Sand</td>
<td></td>
<td>Phase II</td>
<td>Bed Forms</td>
<td>Rosgen C E Regime</td>
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</table>
Bedload transport summary

Sediment entrainment and bedload transport have considerable uncertainty in prediction – uncertainty increases with gradient

- Sand bed streams – $D_{84}$ may move constantly
- Gravel bed pool-riffle streams - $D_{84}$ may move every few years
- Steep boulder step-pool streams - $D_{84}$ may not move for decades
Presentation outline

Background
• Bedload transport
• Channel types and bed mobility/stability

Why do bed stability-mobility analysis?

Flow hydraulics and sediment entrainment

Design application
• Bed mobility
• Bed stability
Stimson Creek Width ratio = 1.0
Slope = 2.2% (5%)

Note regrade
Original profile
Resulting profile

Culvert too narrow, bed material too small.

Prevent bed failure
Prevent structure failure

Upstream aggradation of gravel bedload can contribute to downstream degradation and structure failure.
Bed mobility and stability considerations?

- Key bed or grade control features
  - steps, particle clusters
- Bank material
- Floodplain contraction
  - entrenchment ratio high
  - floodplain conveyance high
Presentation outline

Background
- Bedload transport
- Channel types and bed mobility/stability

Why do bed stability-mobility analysis?

Flow hydraulics and sediment entrainment

Design application
- Bed mobility
- Bed stability
Factors affecting motion

**Resisting Factors:**
- particle size
- particle shape
- particle density
- pivot angle
- packing of particles
- orientation of particles
- sorting of sediments
- distribution of bedforms
- exposure to flow

**Driving Forces:**
- velocity
- flow depth
- slope
- turbulence

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*Flow direction*
Quantifying hydrodynamic forces

Unit Discharge

\[ q = \frac{Q}{w} \]

Total bed shear stress

\[ \tau = \gamma \cdot R \cdot S \]

Flow Width, \( w \)

Discharge – \( Q \)

Slope - \( S \)

Wetted Perimeter - \( P \)

Flow Area - \( A \)

\[ R = \frac{A}{P} \]

Channel substrate within an embedded circular culvert.
Early effort to define motion

Shields (1936) for UNIFORM grains on flat bed

\[
\tau^*_{cri} = \frac{\tau_{cri}}{\gamma(G-1)D_i} = \frac{\gamma RS}{\gamma(G-1)D_i} = \frac{RS}{(G-1)D_i}
\]

\( \tau^*_{cri} \) = critical Shields stress
\( \tau_{cri} = \) critical shear stress - particle begins to move
\( \gamma = \) unit weight of water
\( R = \) hydraulic radius
\( S = \) stream slope
\( G = \) specific gravity of sediment
\( D_i = \) sediment particle size of interest
Table 2. Entrainment thresholds for different particle sizes (modified from Julien, 1995). The Shields parameter and critical shear stress values are for the smallest number in the particle-size interval.

<table>
<thead>
<tr>
<th>Entrainment</th>
<th>threshold</th>
<th>table</th>
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</thead>
<tbody>
<tr>
<td>Particle size classification</td>
<td>Particle size, $D_s$ (mm)</td>
<td>angle of repose, $\phi$ (degrees)</td>
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<td>very large boulders</td>
<td>&gt; 2048</td>
<td>42</td>
</tr>
<tr>
<td>large boulders</td>
<td>1024-2048</td>
<td>42</td>
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<tr>
<td>medium boulders</td>
<td>512-1024</td>
<td>42</td>
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<td>small boulders</td>
<td>256-512</td>
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<tr>
<td>large cobbles</td>
<td>128-256</td>
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<td>small cobbles</td>
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<td>very coarse gravels</td>
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<td>coarse gravels</td>
<td>16-32</td>
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<tr>
<td>medium gravels</td>
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<tr>
<td>fine gravels</td>
<td>4-8</td>
<td>35</td>
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<tr>
<td>very fine gravels</td>
<td>2-4</td>
<td>33</td>
</tr>
<tr>
<td>very coarse sands</td>
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<td>coarse sands</td>
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<tr>
<td>medium sands</td>
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<td>30</td>
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<td>fine sands</td>
<td>0.125-0.25</td>
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<td>coarse silt</td>
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</tr>
<tr>
<td>medium silt</td>
<td>0.0156-0.0313</td>
<td>30</td>
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</tbody>
</table>

Equations used to determine Shield’s parameter:

- $\tau^* = 0.25 \left(25296D_s\right)^{0.6} \tan \phi$ when $0.012 \text{ mm} < D < 0.75 \text{ mm}$ (medium silt to coarse sand)
- $\tau^* = 0.013 \left(25296D_s\right)^{0.4} \tan \phi$ when $0.75 \text{ mm} < D < 2 \text{ mm}$ (coarse sand to very coarse sand)
- $\tau^* = 0.06 \tan \phi$ when $D > 2 \text{ mm}$ (gravel, cobble, and boulder)
Application

<table>
<thead>
<tr>
<th>Resisting force</th>
<th>Driving force</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^*<em>{cri} = \frac{\tau</em>{cri}}{\gamma(G-1)D_i}$</td>
<td>$\tau = \gamma \cdot R \cdot S$</td>
</tr>
<tr>
<td>$\tau_{cri} = \tau^*_{cri} \gamma (G-1)D_i$</td>
<td></td>
</tr>
</tbody>
</table>

If $\tau > \tau_{cri}$, particle will move
If $\tau < \tau_{cri}$, particle will not move
Real stream beds are NOT UNIFORM
Hiding/exposure for mixed grain sizes

Smaller particles shielded behind larger particles
(less mobile than uniform bed)

Larger particles project into flow
(more mobile than uniform bed)
Effects of the hiding/exposure factor

Modification of Shields by Komar (1987, 1996)
Hiding/exposure factor for beds of mixed sizes

\[ \tau_{cri} = f\left(\frac{D_i}{D_{50}}\right) \]

How big is my particle size compared to the median size on bed?
Modification of Shields
Komar (1987, 1996)

Resisting force

$$\tau_{cri} = \lambda(G - 1)\tau^*_D D_{50}^{0.3} D_{50}^{0.7}$$

$$\lambda(G - 1) = 16,170$$

Driving force

$$\tau = \gamma \cdot R \cdot S$$

If $$\tau > \tau_{cri}$$, particle will move
If $$\tau < \tau_{cri}$$, particle will not move

Most applicable on slopes < 3%, Di/D50 ratios < 25, and R/D84 > 5 (R/D50 >10)
Critical unit discharge
Bathurst (1987)

Resisting force

\[ q_{ci} (m^2/s) = q_{cr} \left[ \frac{D_i}{D_{50}} \right]^b \]

\[ q_{cr} = 0.15 g^{1/2} D_{50}^{3/2} S^{-1.12} \]

\[ b = 1.5 \left[ \frac{D_{84}}{D_{16}} \right]^{-1} \]

If \( q > q_{ci} \), particle will move
If \( q < q_{ci} \), particle will not move

(Most applicable on slopes > 2 to 3%, and R/D84 < 5 and R/D50 < 10)

Driving force

\[ q = \frac{Q}{w} \]
Presentation outline

Background
• Bedload transport
• Channel types and bed mobility/stability

Why do bed stability-mobility analysis?

Flow hydraulics and sediment entrainment

Design application
• Bed mobility
• Bed stability
Bed mobility analysis - concepts

- Compares design channel bed to reference reach
- $D_{84}$ particle sizes should mobilize at the same flow in both channels
- Channel roughness, channel form, and bed mobility are controlled by $D_{84}$ particles sizes
- Comparative analysis based on reference reach calibrates the model; therefore analysis is not sensitive to hydrology, hydraulics and model inputs or assumptions
Procedure for bed mobility analysis: Reference reach

1. Determine flow hydraulics
   - Calculate shear stress and/or unit discharge
   - Active channel
   - Range of discharges: $Q_{bf}, Q_{1.5}-Q_{100}$

2. Calculate critical shear stress and/or unit discharge
   - $D_{84}$ particle size
   - Entire particle size distribution

3. Determine when particle mobility occurs
Procedure for bed mobility analysis: Design channel

4. Determine flow hydraulics
   - Calculate shear stress and/or unit discharge
   - Range of discharges: $Q_{bf}$, $Q_{1.5}$-$Q_{100}$

5. Calculate critical shear stress and/or unit discharge
   - $D_{84}$ particle size
   - Entire particle size distribution

6. Determine when particle mobility occurs
Procedure for bed mobility analysis: Adjust design bed as needed

7. Compare reference and design beds
   - Does $D_{84}$ mobility occur at the same discharge?
   - If yes, proceed to stability analysis
   - If no, adjust particle sizes in the design channel until mobility occurs at the same discharge as in the reference reach

8. If the particle size adjustment exceeds 25%, reevaluate design and make further adjustments
Bed stability analysis - concepts

- Key pieces provide stable banks and bed forms
- Key pieces are critical for bank stability and form due to lack of vegetation in culverts and under bridges
- Key pieces are permanent - up to stability design flow
- What is stability design flow? $Q_{100}$ or higher
Procedure for bed stability analysis

- Use same procedures as for mobility analysis
  - Shear Stress
  - Unit Discharge

- Except use $D_{84}$ from key pieces (10 largest particles) in reference reach
Sediment mobility (D84) and sediment stability (key pieces)

Example: Trout Trib at Cty U
**Sediment mobility**

*(Excel Example – Shear Stress – XS 1 Ref Reach)*

| Recurrence Interval | Discharge, Q (ft³/s) | Flood plain n value | Channel n value | Channel slope, S₀ | Energy slope, Sₑ | Total flow width, W₁ (ft) | Channel flow width, W₂ (ft) | Total hydraulic radius, Rₚ (ft) | Channel Hydraulic Radius, Rₑ (ft) | Total boundary shear stress, τₑ (lb/ft²) | Channel boundary shear stress, τₖ (lb/ft²) | D₉₀ (mm) | D₈₄ (mm) | Angle of repose | Shield’s entrainment for $\tau^*_D$ (c) | Critical Shear Stress to Entrain $D_{84}$ Particle Size, $\tau_{C-D84}$ (lb/ft²) | $D_{84}$ Particle Mobile (yes/no) |
|---------------------|----------------------|---------------------|-----------------|------------------|------------------|--------------------------|-----------------------------|--------------------------------|--------------------------------|--------------------------------|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 20                  | 0.100                | 0.040               | 0.0110          | 0.0114           | 15.01            | 15.01                    | 0.59                        | 0.59                          | 0.42                          | 0.42                          | 35                | 80              | 41              | 0.052                      | 0.79                        | no                           |
| 25                  | 0.100                | 0.040               | 0.0110          | 0.0114           | 15.35            | 15.35                    | 0.66                        | 0.66                          | 0.47                          | 0.47                          | 35                | 80              | 41              | 0.052                      | 0.79                        | no                           |
| 1.5                 | 30                   | 0.040               | 0.0110          | 0.0114           | 15.63            | 15.63                    | 0.73                        | 0.73                          | 0.52                          | 0.52                          | 35                | 80              | 41              | 0.052                      | 0.79                        | no                           |
| 2                   | 40                   | 0.040               | 0.0110          | 0.0114           | 16.14            | 16.14                    | 0.85                        | 0.85                          | 0.60                          | 0.60                          | 35                | 80              | 41              | 0.052                      | 0.79                        | no                           |
| 5                   | 67                   | 0.040               | 0.0110          | 0.0114           | 17.29            | 17.29                    | 1.10                        | 1.10                          | 0.79                          | 0.79                          | 35                | 80              | 41              | 0.052                      | 0.79                        | no                           |
| 10                  | 85                   | 0.100               | 0.040           | 0.0110           | 17.95            | 17.95                    | 1.24                        | 1.24                          | 0.88                          | 0.88                          | 35                | 80              | 41              | 0.052                      | 0.79                        | yes                          |
| 25                  | 106                  | 0.100               | 0.040           | 0.0110           | 23.73            | 18.64                    | 1.10                        | 1.38                          | 0.78                          | 0.98                          | 35                | 80              | 41              | 0.052                      | 0.79                        | yes                          |
| 50                  | 121                  | 0.100               | 0.040           | 0.0110           | 35.23            | 18.96                    | 0.85                        | 1.47                          | 0.61                          | 1.05                          | 35                | 80              | 41              | 0.052                      | 0.79                        | yes                          |
| 100                 | 136                  | 0.100               | 0.040           | 0.0110           | 53.59            | 19.22                    | 0.65                        | 1.56                          | 0.46                          | 1.11                          | 35                | 80              | 41              | 0.052                      | 0.79                        | yes                          |
| 500                 | 166                  | 0.100               | 0.040           | 0.0096           | 75.32            | 19.64                    | 0.62                        | 1.68                          | 0.44                          | 1.20                          | 35                | 80              | 41              | 0.052                      | 0.79                        | yes                          |

$D_{84}$ mobilizes in reference reach between 67 and 85 cfs (>est. 5-yr flood)
D$_{84}$ mobilizes in middle of culvert between 85 and 106 cfs (>est. 10-yr flood)
Sediment mobility
(Excel Example – Shear Stress – XS 3b Middle 16’ Wide Box Culvert)

With 25% increase in bed material size, $D_{84}$ mobilizes in middle of culvert between 121 and 136 cfs (>est. 50-yr flood)

<table>
<thead>
<tr>
<th>Recurrence Interval</th>
<th>Discharge, Q (ft^3/s)</th>
<th>Floodplain n value</th>
<th>Channel n value</th>
<th>Channel slope, $S_c$</th>
<th>Energy slope, $S_e$</th>
<th>Total flow width, $W_t$ (ft)</th>
<th>Channel flow width, $W_c$ (ft)</th>
<th>Total hydraulic radius, $R_h$ (ft)</th>
<th>Channel Hydraulic Radius, $R_{ch}$ (ft)</th>
<th>Total boundary shear stress, $\tau_b$ (lb/ft^2)</th>
<th>Channel boundary shear stress, $\tau_c$ (lb/ft^2)</th>
<th>$D_{50}$ (mm)</th>
<th>$D_{84}$ (mm)</th>
<th>Angle of repose, $\phi$</th>
<th>Shield’s entrainment for $\tau^*_D$, c</th>
<th>Critical Shear Stress to Entrain $D_{84}$ Particle Size, $\tau_{c-D_{84}}$ (lb/ft^2)</th>
<th>$D_{64}$ Particle Mobile (yes/no)</th>
</tr>
</thead>
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<td>0.040</td>
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<td>40</td>
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<td>0.95</td>
<td>Yes</td>
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</tbody>
</table>
Sediment mobility
(Excel Ex – Shear Stress – 16’ Box Culvert Adjustment +25%)

Ref Reach (XS1): $D_{84}$ mobile at 85 cfs ($Q_{10}$)
Initial Bed: $D_{84}$ mobile at 106 cfs ($Q_{25}$)
Adjusted Bed: $D_{84}$ mobile at 136 cfs ($Q_{100}$)

<table>
<thead>
<tr>
<th>$D_{50}$ (mm)</th>
<th>$D_{84}$ (mm)</th>
<th>Angle of repose $\phi$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>80</td>
<td>41</td>
<td>initial reference reach particle size</td>
</tr>
<tr>
<td>43.8</td>
<td>100.0</td>
<td>40</td>
<td>adjusted particle sizes in design channel</td>
</tr>
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</table>

25 percent particle size adjustment
Sediment stability
(Excel Example – Shear Stress – XS 1 Ref Reach)

<table>
<thead>
<tr>
<th>Recurrence Interval</th>
<th>Discharge, Q (ft³/s)</th>
<th>Channel slope, S₀</th>
<th>Energy slope, Sₑ</th>
<th>Total flow width, W₁ (ft)</th>
<th>Channel flow width, Wₑ (ft)</th>
<th>Total hydraulic radius, Rₑ (ft)</th>
<th>Channel Hydraulic Radius, Rₜ (ft)</th>
<th>Total boundary shear stress, τₑ (lb/ft²)</th>
<th>D₈₄ (mm)</th>
<th>D₈₄ (mm)</th>
<th>Angle of repose, ϕ</th>
<th>Shield’s entrainment for τₑₕ₅₀</th>
<th>Critical Shear Stress to Entrain D₈₄ Particle Size, τₑₕ₈₄ (lb/ft²)</th>
<th>D₈₄ Particle Stable (yes/no)</th>
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<tbody>
<tr>
<td>20</td>
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D₈₄ (12 inches or 305 mm) for key pieces stable at all flows.
D$_{84}$ (12 inches or 305 mm) for key pieces stable at all flows.