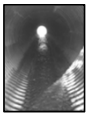
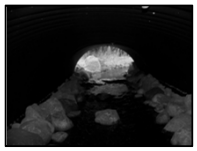
9. Sediment Entrainment & Bed Mobility/Stability Analysis





Mark Weinhold
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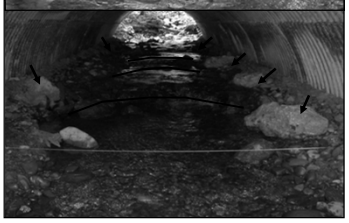
White River National Forest

Dan Cenderelli
USDA Forest Service
Stream Systems Technology Center

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

Relationship between channel type and sediment entrainment/bedload transport

Channel – Bed Type	Relative Mobility	Typical Transport at Bankfull	Structure	Channel Type
Boulder Cobble	Low	Phase I	Steps	Rosgen A Cascade Step Pool
Cobble Gravel		Phase I Phase II	Particle clusters Armor	Rosgen B C Plane Bed Pool Riffle
Sand	High	Phase II	Bed Forms	Rosgen C E Regime

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

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- Channel types and bed mobility/stability

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Flow hydraulics and sediment entrainment

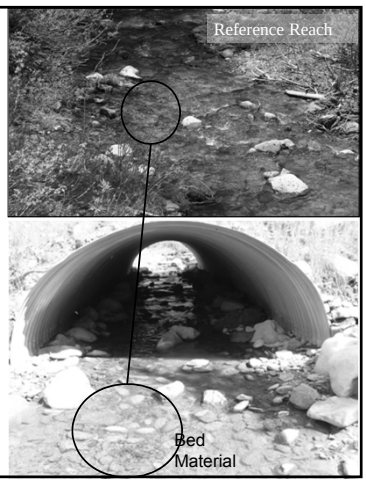
Design application
- Bed mobility
- Bed stability

Prevent bed failure

Culvert too narrow, bed material too small.

Maintain continuity

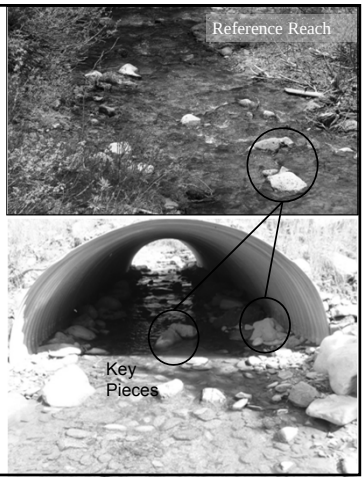
- **Is the MOBILITY of sediment in the design channel and reference reach SIMILAR?**



Maintain continuity

- **Is the MOBILITY of sediment in the design channel and reference reach SIMILAR?**

Are KEY PIECES and grade controls STABLE for the design flow and large floods?



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
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Why do bed stability-mobility analysis?

Flow hydraulics and sediment entrainment

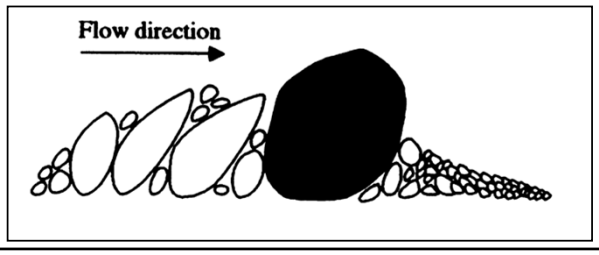
Design application
- Bed mobility
- Bed stability

Factors affecting motion

Resisting Factors:
- particle size
- particle shape
- particle density
- pivot angle

Resisting Factors:
- packing of particles
- orientation of particles
- sorting of sediments
- distribution of bedforms
- exposure to flow

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



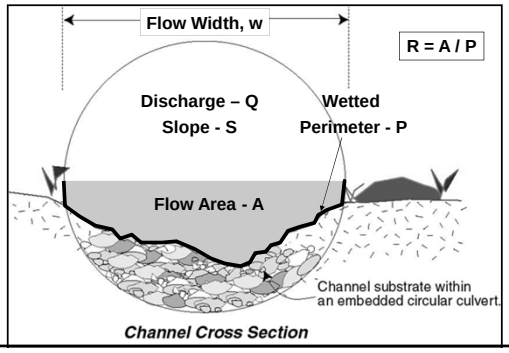
Quantifying hydrodynamic forces

Unit Discharge

$$q = Q / w$$

Total bed shear stress

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



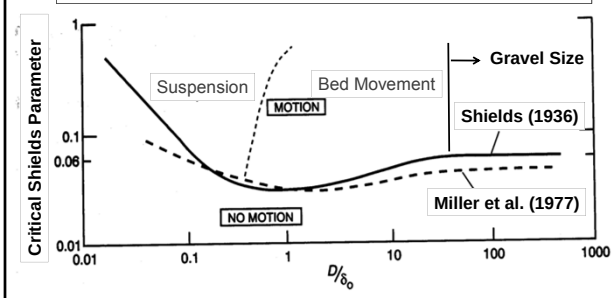
Early effort to define motion

Shields (1936) for UNIFORM grains on flat bed

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

τ^*_{cri} = critical Shields stress
τ_{cri} = critical shear stress - particle begins to move
γ = unit weight of water
R = hydraulic radius
S = stream slope
G = specific gravity of sediment
D_i = sediment particle size of interest

Critical Shear Stress



Entrainment threshold table

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.

Particle size classification	Particle size, D_s (mm)	angle of repose, ϕ (degrees)	Shield's parameter[a], τ_*	critical shear stress, τ_{cr} (N/m^2)
very large boulders	> 2048	42	0.054	1789
large boulders	1024-2048	42	0.054	895
medium boulders	512-1024	42	0.054	447
small boulders	256-512	42	0.054	224
large cobbles	128-256	42	0.054	112
small cobbles	64-128	41	0.052	54.0
very coarse gravels	32-64	40	0.050	26.1
coarse gravels	16-32	38	0.047	12.1
medium gravels	8-16	36	0.044	5.64
fine gravels	4-8	35	0.042	2.72
very fine gravels	2-4	33	0.039	1.26
very coarse sands	1-2	32	0.029	0.48
coarse sands	0.5-1.0	31	0.033	0.27
medium sands	0.25-0.50	30	0.048	0.19
fine sands	0.125-0.25	30	0.072	0.15
very fine sands	0.0625-0.125	30	0.109	0.11
coarse silt	0.0313-0.0625	30	0.165	0.084
medium silt	0.0156-0.0313	30	0.250	0.063

a. equations used to determine Shield's parameter:

$\tau_* = 0.25\,(25296D)^{-0.6}\tan\phi$ when 0.012 mm < D < 0.75 mm (medium silt to coarse sand)

$\tau_* = 0.013\,(25296D)^{0.4}\tan\phi$ when 0.75 mm < D < 2 mm (coarse sand to very coarse sand)

$\tau_* = 0.06\tan\phi$ when D ≥ 2 mm (gravels, cobbles, and boulders)

Application

Resisting force

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

Driving force

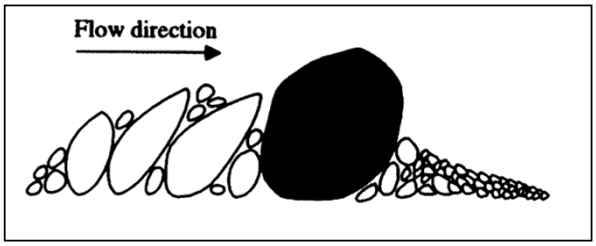
$$\tau = \gamma \cdot R \cdot S$$

$$\tau_{cri} = \tau^*_{cri}\ \gamma(G-1)D_i$$

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

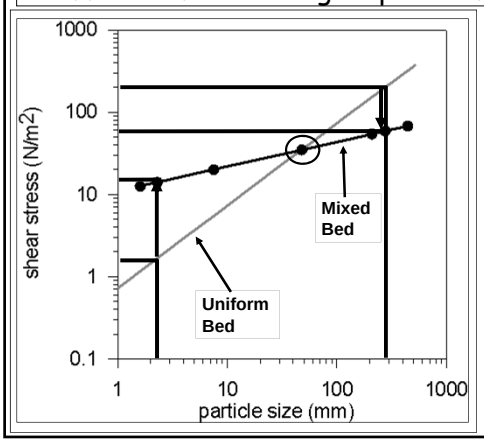
Real stream beds are NOT UNIFORM

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, 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

$$\tau_{cri} = \lambda(G-1)\tau^*_{D50} D_i^{0.3} D_{50}^{0.7}$$

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

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%, D_i/D_{50} ratios < 25, $R/D_{84} > 5$, $R/D_{50} > 10$)

Critical unit discharge
Bathurst (1987)

Resisting force

$q_{ci}(m^2/s) = q_{cr}[D_i / D_{50}]^{b}$

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

$b = 1.5\, [D_{84} / D_{16}]^{-1}$

Driving force

$q = Q / w$

If $q > q_{ci}$, particle will move
If $q < q_{ci}$, particle will not move

(Most applicable on slopes > 2 to 3%, and $R/D_{84} < 5$ and $R/D_{50} < 10$)

Presentation outline

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

Why do bed stability-mobility analysis?

Flow hydraulics and sediment entrainment

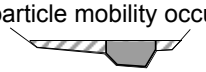
Design application
- Bed mobility
- Bed stability

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

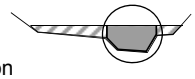
Procedure for bed mobility analysis: Reference reach

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

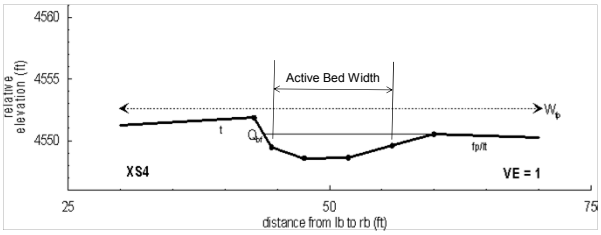
7. Compare reference and design beds
   - Does D_{84} mobility occur at the same discharge?
   - If yes, proceed to stability analysis
   - If no, adjust particle sizes in the design channel until mobility occurs at the same discharge as in the reference reach
8. If the particle size adjustment exceeds 25%, reevaluate design and make further adjustments

Procedure for bed mobility w/shear stress

1. **Determine flow hydraulics (unit discharge) for different discharges in the reference reach via HEC-RAS, WinXSPro, etc.**
2. **Calculate threshold unit discharge for the D84 particle size in the reference reach**
3. **Determine discharge when D_{84} moves in the reference reach**

Procedure for bed mobility w/shear stress

Reference Reach Cross Section:



Pebble Count Results: D_{16} = 37 mm
D_{50} = 100 mm
D_{84} = 208 mm

Gradient, S = 0.0353

Procedure for bed mobility w/shear stress

STEP 1 – Reference Reach Hydraulics

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

Hydraulics					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Energy slope, S_e	Chan-nel flow width, W_c (ft)	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**
A. Reference reach cross section: XS4					
	70	0.0269	14.66	1.16	**1.95**
2	98	0.0299	15.51	1.28	**2.39**
	100	0.0300	15.54	1.29	**2.42**
bf	110	0.0301	15.54	1.35	**2.54**
	130	0.0304	15.54	1.46	**2.76**
5	157	0.0306	15.54	1.59	**3.03**

Procedure for bed mobility w/shear stress

STEP 2 – Reference Reach Threshold Shear

$$\tau_{c84} = \gamma(G-1)\tau^*_{D50} D_{84}^{0.3} D_{50}^{0.7}$$

Hydraulics					Particle Mobility/Stability				
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Energy slope, S_e	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Shield's entrain-ment for τ^*_{D50}[c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (lb/ft^2)[d]**	D_{84} Particle Mobile (yes/no)
A. Reference reach cross section:									
	70	0.0269	1.16	**1.95**	100	208	0.054	**2.27**	
2	98	0.0299	1.28	**2.39**	100	208	0.054	**2.27**	
	100	0.0300	1.29	**2.42**	100	208	0.054	**2.27**	
bf	110	0.0301	1.35	**2.54**	100	208	0.054	**2.27**	
	130	0.0304	1.46	**2.76**	100	208	0.054	**2.27**	
5	157	0.0306	1.59	**3.03**	100	208	0.054	**2.27**	
	STEP 1				**STEP 2**				**STEP 3**

Procedure for bed mobility w/shear stress

STEP 3 – Reference Reach D84 Moving?

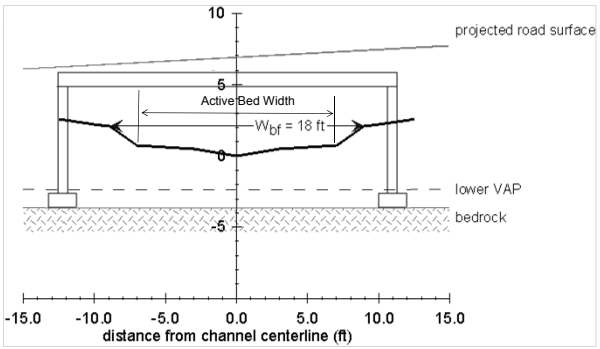
$$\tau_{c84} = \gamma(G-1)\tau^*_{D50} D_{84}^{0.3} D_{50}^{0.7}$$

Hydraulics					Particle Mobility/Stability				
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Energy slope, S_e	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Shield's entrain-ment for τ^*_{D50}[c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (lb/ft^2)[d]**	D_{84} Particle Mobile (yes/no)
A. Reference reach cross section:									
	70	0.0269	1.16	**1.95**	~~100~~	~~208~~	~~0.054~~	**2.27**	**NO**
2	98	0.0299	1.28	**2.39**	100	208	0.054	**2.27**	**YES**
	100	0.0300	1.29	**2.42**	100	208	0.054	**2.27**	**YES**
bf	110	0.0301	1.35	**2.54**	100	208	0.054	**2.27**	**YES**
	130	0.0304	1.46	**2.76**	100	208	0.054	**2.27**	**YES**
5	157	0.0306	1.59	**3.03**	100	208	0.054	**2.27**	**YES**
	STEP 1				**STEP 2**				**STEP 3**

Procedure for bed mobility w/shear stress

CONSPAN

23.3 ft Interior Width, Design Slope = 0.0394



Procedure for bed mobility w/shear stress

4. **Determine flow hydraulics (boundary shear stress) for different discharges in the design channel via HEC-RAS, WinXSPro, etc.**
5. **Calculate threshold critical shear stress for the D84 particle size in the design channel**
6. **Determine discharge when D_{84} moves in the design channel**

Procedure for bed mobility w/shear stress

STEP 4 – Design Channel Hydraulics

Hydraulics				
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Energy slope, S_e	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**
B. Preliminary design channel for 23.3 ft wide				
	70	0.0394	1.02	**2.51**
2	98	0.0394	1.21	**2.97**
	100	0.0394	1.22	**3.00**
bf	110	0.0394	1.28	**3.15**
	130	0.0394	1.40	**3.44**
5	157	0.0394	1.56	**3.85**

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

Procedure for bed mobility w/shear stress

STEP 5 – Design Channel Threshold Shear

$$\tau_{c84} = \gamma(G-1)\tau^*_{D50} D_{84}^{0.3} D_{50}^{0.7}$$

Hydraulics					Particle Mobility/Stability				
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Energy slope, S_e	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Shield's entrain-ment for τ^*_{D50}[c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (lb/ft^2)[d]**	D_{84} Particle Mobile (yes/no)
B. Preliminary design channel for 23.3 ft wide Conspan structure									
	70	0.0394	1.02	**2.51**	100	208	0.054	**2.27**	
2	98	0.0394	1.21	**2.97**	100	208	0.054	**2.27**	
	100	0.0394	1.22	**3.00**	100	208	0.054	**2.27**	
bf	110	0.0394	1.28	**3.15**	100	208	0.054	**2.27**	
	130	0.0394	1.40	**3.44**	100	208	0.054	**2.27**	
5	157	0.0394	1.56	**3.85**	100	208	0.054	**2.27**	

STEP 4 | **STEP 5** | **STEP 6**

Procedure for bed mobility w/shear stress

STEP 6 – Design Channel D84 Moving?

$$\tau_{c84} = \gamma(G-1)\tau^*_{D50} D_{84}^{0.3} D_{50}^{0.7}$$

Hydraulics					Particle Mobility/Stability				
Recur-rence Interval	Dis-charge, Q (ft³/s)	Energy slope, S_e	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft²)[b]**	D_{50} (mm)	D_{84} (mm)	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (lb/ft²)[d]**	D_{84} Particle Mobile (yes/no)
B. Preliminary design channel for 23.3 ft wide Conspan structure									
	70	0.0394	1.02	**2.51**	100	208	0.054	2.27	**YES**
2	98	0.0394	1.21	**2.97**	100	208	0.054	2.27	**YES**
	100	0.0394	1.22	**3.00**	100	208	0.054	2.27	**YES**
bf	110	0.0394	1.28	**3.15**	100	208	0.054	2.27	**YES**
	130	0.0394	1.40	**3.44**	100	208	0.054	2.27	**YES**
5	157	0.0394	1.56	**3.85**	100	208	0.054	2.27	**YES**

STEP 4 **STEP 5** **STEP 6**

Procedure for bed mobility w/shear stress

7. **If particle mobility is different between the design channel and the reference channel, adjust particle sizes in the design channel until similar particle mobility is achieved**
8. **If the particle size adjustment exceeds 25%, reevaluate design and make adjustments**

Procedure for bed mobility w/shear stress

STEP 7: Adjust particle sizes in Design Channel (if necessary)

Hydraulics					Particle Mobility/Stability				
Recur-rence Interval	Dis-charge, Q (ft³/s)	Energy slope, S_e	Active Channel Hydraulic Radius, R_a (ft)	**Channel boundary shear stress, τ_c (lb/ft²)[b]**	D_{50} (mm)	D_{84} (mm)	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (lb/ft²)[d]**	D_{84} Particle Mobile (yes/no)
C. Adjusted stream simulation design channel for 23.3 ft wide Conspan structure with a channel-									
	70	0.0394	1.02	**2.51**	124	258	0.054	2.82	no
2	98	0.0394	1.21	**2.97**	124	258	0.054	2.82	yes
	100	0.0394	1.22	**3.00**	124	258	0.054	2.82	yes
bf	110	0.0394	1.28	**3.15**	124	258	0.054	2.82	yes
	130	0.0394	1.40	**3.44**	124	258	0.054	2.82	yes
5	157	0.0394	1.56	**3.85**	124	258	0.054	2.82	yes

24 % Particle Size increase

Gives similar mobility and excess shear

Mobility/Stability Methods

Mobility (Similar Movement)

Stability (No Movement)

Check this Method now

Unit Discharge

$$q_{ci} = 0.15 g^{1/2} D_{50}^{1.5} S^{-1.12} [D_i / D_{50}]^b$$

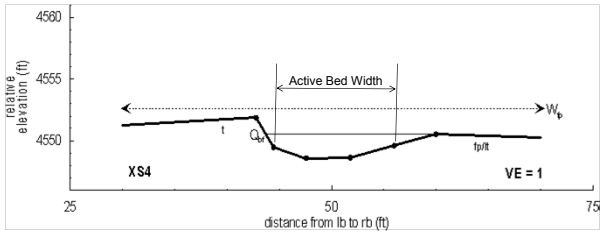
Shear Stress

$$\tau_{ci} = \gamma(G-1)\tau^*_{D50} D_i^{0.3} D_{50}^{0.7}$$

24 % Particle Size increase

Procedure for bed mobility w/unit discharge

Reference Reach Cross Section:



Pebble Count Results: D_{16} = 37 mm
D_{50} = 100 mm
D_{84} = 208 mm

Gradient, S = 0.0353

Procedure for bed mobility w/unit discharge

Threshold

$$q_{c84} = 0.15 g^{1/2} D_{50}^{1.5} S^{-1.12} [D_{84}/D_{50}]^b$$

$$b = 1.5[D_{84}/D_{16}]^{-1}$$

Driving force

$$q = Q/w$$

If $q > q_{ci}$, particle will move
If $q < q_{ci}$, particle will not move

Most applicable on slopes between 2 and 5 %,
$70 < D_{50} < 140$ mm, $150 < D_{84} < 250$ mm, $R/D_{84} < 5$

Procedure for bed mobility w/unit discharge

1. **Determine flow hydraulics (unit discharge) for different discharges in the reference reach via HEC-RAS, WinXSPro, etc.**
2. **Calculate threshold unit discharge for the D84 particle size in the reference reach**
3. **Determine discharge when D_{84} moves in the reference reach**

Procedure for bed mobility w/unit discharge

STEP 1 – Reference Reach Hydraulics

Hydraulics				
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Active Channel Width Dis-charge, Q_a (ft^3/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Dis-charge, q_a (ft^2/s) ^{b}**
A. Reference reach cross section: XS4				
	70	62	11.00	**5.68**
2	98	82	11.00	**7.48**
	100	84	11.00	**7.60**
bf	110	90	11.00	**8.18**
	130	102	11.00	**9.31**
5	157	119	11.00	**10.79**

$$q = Q/w$$

Procedure for bed mobility w/unit discharge

STEP 2 – Reference Reach Threshold Unit Discharge

$$q_{c84} = 0.15 g^{1/2} D_{50}^{1.5} S^{-1.12} [D_{84} / D_{50}]^b$$

$$b = 1.5[D_{84}/D_{16}]^{-1}$$

Hydraulics									Particle Mobility Stability	
Recurrence Interval	Discharge, Q (ft³/s)	Active Channel Width Discharge, Q_a (ft³/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Discharge, q_a (ft²/s)** [b]	Channel slope, S_c	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	**Critical Unit Discharge to Entrain D_{84} Particle Size, $q_{c\text{-}D84}$ (ft²/s)**[e]	D_{84} Particle Mobile (yes/no)
A. Reference reach cross section: XS4										
	70	62	11.00	**5.68**	0.0353	37	100	208	**8.23**	
2	98	82	11.00	**7.48**	0.0353	37	100	208	**8.23**	
	100	84	11.00	**7.60**	0.0353	37	100	208	**8.23**	
bf	110	90	11.00	**8.18**	0.0353	37	100	208	**8.23**	
	130	102	11.00	**9.31**	0.0353	37	100	208	**8.23**	
5	157	119	11.00	**10.79**	0.0353	37	100	208	**8.23**	

STEP 1 | **STEP 2** | **STEP 3**

Procedure for bed mobility w/unit discharge

STEP 3 – Reference Reach D84 Moving?

$$q_{c84} = 0.15 g^{1/2} D_{50}^{1.5} S^{-1.12} [D_{84} / D_{50}]^b$$

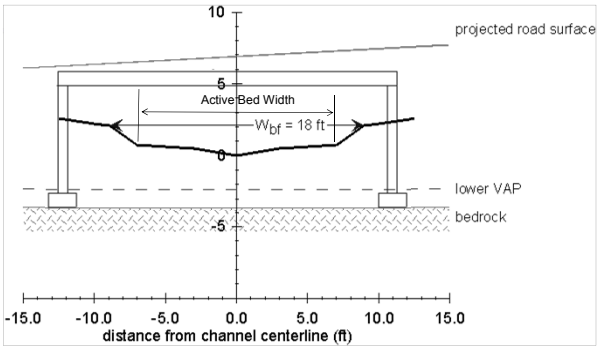
Hydraulics									Particle Mobility Stability	
Recurrence Interval	Discharge, Q (ft³/s)	Active Channel Width Discharge, Q_a (ft³/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Discharge, q_a (ft²/s)** [b]	Channel slope, S_c	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	**Critical Unit Discharge to Entrain D_{84} Particle Size, $q_{c\text{-}D84}$ (ft²/s)**[e]	D_{84} Particle Mobile (yes/no)
A. Reference reach cross section: XS4										
	70	62	11.00	**5.68**	0.0353	37	100	208	**8.23**	**NO**
2	98	82	11.00	**7.48**	0.0353	37	100	208	**8.23**	**NO**
	100	84	11.00	**7.60**	0.0353	37	100	208	**8.23**	**NO**
bf	110	90	11.00	**8.18**	0.0353	37	100	208	**8.23**	**NO**
	130	102	11.00	**9.31**	0.0353	37	100	208	**8.23**	**YES**
5	157	119	11.00	**10.79**	0.0353	37	100	208	**8.23**	**YES**

STEP 1 | **STEP 2** | **STEP 3**

Procedure for bed mobility w/unit discharge

CONSPAN

23.3 ft Interior Width, Design Slope = 0.0394



Procedure for bed mobility w/unit discharge

4. **Determine flow hydraulics (unit discharge) for different discharges in the design channel via HEC-RAS, WinXSPro, etc.**
5. **Calculate threshold unit discharge for the D84 particle size in the design channel**
6. **Determine discharge when D_{84} moves in the design channel**

Procedure for bed mobility w/unit discharge

STEP 4 – Design Channel Hydraulics

$$q = Q / w$$

Hydraulics				
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Active Channel Width Dis-charge, Q_a (ft^3/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Dis-charge, q_a (ft^2/s) [b]**
B. Preliminary stream simulation design chan				
	70	70	14.00	**5.00**
2	98	98	14.00	**7.00**
	100	100	14.00	**7.14**
bf	110	110	14.00	**7.86**
	130	130	14.00	**9.29**
5	157	157	14.00	**11.21**

Procedure for bed mobility w/unit discharge

STEP 5 – Design Channel Threshold Unit Discharge

$$q_{c84} = 0.15 g^{1/2} D_{50}^{1.5} S^{-1.12} [D_{84} / D_{50}]^b$$

$$b = 1.5 [D_{84} / D_{16}]^{-1}$$

Hydraulic					Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Active Channel Width Dis-charge, Q_a (ft^3/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Dis-charge, q_a (ft^2/s) [b]**	Channel slope, S_c	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	**Critical Unit Discharge to Entrain D_{84} Particle Size, $q_{c\text{-}D84}$ (ft^2/s)[e]**	D_{84} Particle Mobile (yes/no)
B. Preliminary stream simulation design channel for 23.3 ft wide Conspan structure with a channel-bed gr										
	70	70	14.00	**5.00**	0.0394	37	100	208	**7.28**	
2	98	98	14.00	**7.00**	0.0394	37	100	208	**7.28**	
	100	100	14.00	**7.14**	0.0394	37	100	208	**7.28**	
bf	110	110	14.00	**7.86**	0.0394	37	100	208	**7.28**	
	130	130	14.00	**9.29**	0.0394	37	100	208	**7.28**	
5	157	157	14.00	**11.21**	0.0394	37	100	208	**7.28**	

STEP 4 | **STEP 5** | **STEP 6**

Procedure for bed mobility w/unit discharge

STEP 6 – Design Channel D84 Moving?

$$q_{c84} = 0.15 g^{1/2} D_{50}^{1.5} S^{-1.12} [D_{84} / D_{50}]^b$$

Hydraulics					Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Active Channel Width Dis-charge, Q_a (ft^3/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Dis-charge, q_a (ft^2/s) [b]**	Channel slope, S_c	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	**Critical Unit Discharge to Entrain D_{84} Particle Size, $q_{c\text{-}D84}$ (ft^2/s)[e]**	D_{84} Particle Mobile (yes/no)
B. Preliminary stream simulation design channel for 23.3 ft wide Conspan structure with a channel-bed gr										
	70	70	14.00	**5.00**	0.0394	37	100	208	**7.28**	**NO**
2	98	98	14.00	**7.00**	0.0394	37	100	208	**7.28**	**NO**
	100	100	14.00	**7.14**	0.0394	37	100	208	**7.28**	**NO**
bf	110	110	14.00	**7.86**	0.0394	37	100	208	**7.28**	**YES**
	130	130	14.00	**9.29**	0.0394	37	100	208	**7.28**	**YES**
5	157	157	14.00	**11.21**	0.0394	37	100	208	**7.28**	**YES**

STEP 4 | **STEP 5** | **STEP 6**

Procedure for bed mobility w/unit discharge

7. **If particle mobility is different between the design channel and the reference channel, adjust particle sizes in the design channel until similar particle mobility is achieved**

8. **If the particle size adjustment exceeds 25%, reevaluate design and make adjustments**

Procedure for bed mobility w/unit discharge

STEP 7: Adjust particle sizes in Design Channel (if necessary)

Hydraulics					Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Active Channel Width Dis-charge, Q_a (ft^3/s)	Active Channel Width, W_a (ft)	**Active Channel Unit Dis-charge, q_b (ft^2/s) [b]**	Channel slope, S_c	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	**Critical Unit Discharge to Entrain D_{84} Particle Size, q_{c-D84} (ft^2/s)[e]**	D_{84} Particle Mobile (yes/no)
C. Adjusted stream simulation design channel for 23.3 ft wide Conspan structure with a channel-bed grad										
	70	70	14.00	**5.00**	0.0394	40	109	227	**8.28**	no
2	98	98	14.00	**7.00**	0.0394	40	109	227	**8.28**	no
	100	100	14.00	**7.14**	0.0394	40	109	227	**8.28**	no
bf	110	110	14.00	**7.86**	0.0394	40	109	227	**8.28**	no
	130	130	14.00	**9.29**	0.0394	40	109	227	**8.28**	yes
5	157	157	14.00	**11.21**	0.0394	40	109	227	**8.28**	yes

9 % Particle Size increase

Gives similar mobility and excess energy

Procedure for bed mobility w/unit discharge

Hogback Creek Example, Bed Mobility Comparison and Summary

Parameter	Selected Percentile Particle Sizes				
	D16 (mm)	D50 (mm)	D84 (mm)	D95 (mm)	
A. Reference Reach Pebble Count / Initial Design Mix	37	100	208	322	
B. Adjusted bed design mix - mobility analyis with **CRITICAL SHEAR**	46	124	258	400	**24%** ↑
C. Adjusted bed design mix - moblity analysis with **CRITICAL UNIT DISCHARGE**	40	109	227	351	**9%** ↑

Bed stability analysis - concepts

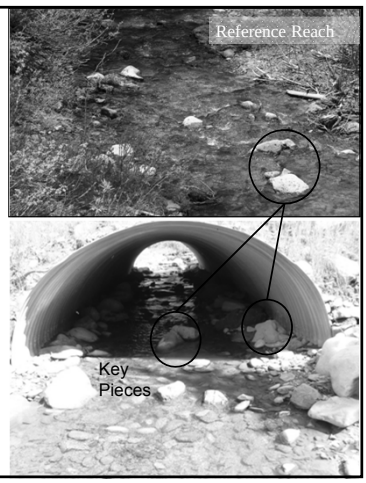
- Key pieces provide stable banks and bed forms
- Key pieces are critical for bank stability and form due to lack of vegetation in culverts and under bridges
- Key pieces are permanent - up to stability design flow
- What is stability design flow? Q_{100} or higher

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

Are KEY PIECES and grade controls STABLE for the design flow and large floods?

Essentially the same process as the Mobility Analysis.



Bed Stability Analysis

Ten largest particles measured in the reference reach (Slope segment E, XS4)

particle number	long axis (mm)	inter-mediate axis (mm)	short axis (mm)	average cubic dimension (mm)	long axis/intermediate axis ratio	particle shape; roundness
1	680	430	210	395	1.58	bladed shape; subangular
2	620	470	140	344	1.32	platy shape; subangular
3	680	410	310	442	1.66	elongated shape; subangular
4	570	420	180	351	1.36	bladed shape; subangular
5	530	430	270	395	1.23	bladed shape; subangular
6	550	270	220	320	2.04	elongated shaped; subangular
7	490	260	210	299	1.88	elongated shaped; subangular
8	430	280	110	237	1.54	bladed shape; subangular
9	610	330	120	289	1.85	bladed shape; subangular
10	260	230	170	217	1.13	compact, bladed shape; subangular
average				**329**	**1.56**	

d95 percentile (mm)	**680**	**452**	**292**
d84 percentile (mm)	**654**	**430**	**248**
d50 percentile (mm)	**560**	**370**	**195**
d16 percentile (mm)	**456**	**264**	**129**

average cubic dimension of d95 percentile	**448**
average cubic dimension of d84 percentile	**412**
average cubic dimension of d50 percentile	**343**
average cubic dimension of d16 percentile	**250**

Procedure for bed stability

Hogback Creek Example, Bed Stability Comparison and Summary

Parameter	Selected percentile particle d16 (mm)	d50 (mm)	d84 (mm)	d95 (mm)
A. Reference reach key pieces (XS4, slope segment E, gradient 3.54 percent)	264	370	430	452
B. Initial design of bed key pieces	264	370	430	452
C. Adjusted initial design of bed key pieces based on bed stability analysis using the ***critical shear stress approach***[a]	264	370	430	452
D. Adjusted initial design of bed key pieces based on bed stability analysis using the ***critical unit discharge approach***[b]	264	370	430	452

No size adjustment

No size adjustment