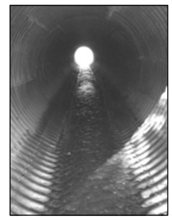
Culvert Design Process

Hydrology
↓
Site Assessment
↓
Alignment and Profile
↓
Bed and Banks
↓
Structure
↓
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

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

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Prevent bed failure

Culvert too narrow, bed material too small.

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

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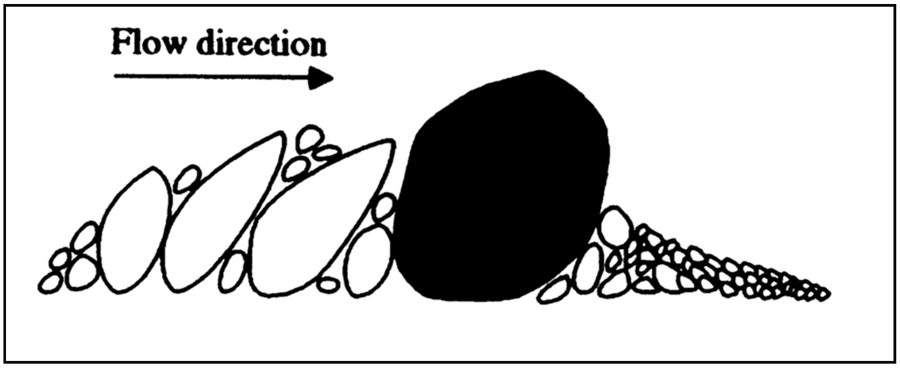
- Bed stability

Factors affecting motion

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

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

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



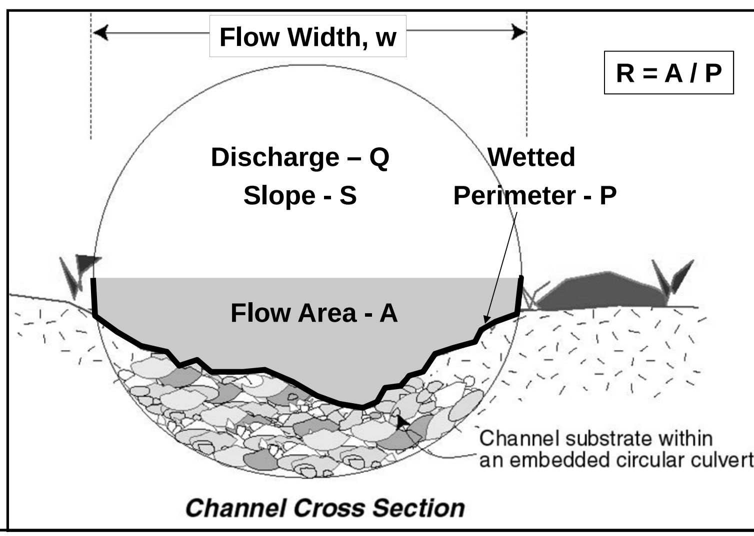
Quantifying hydrodynamic forces

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

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

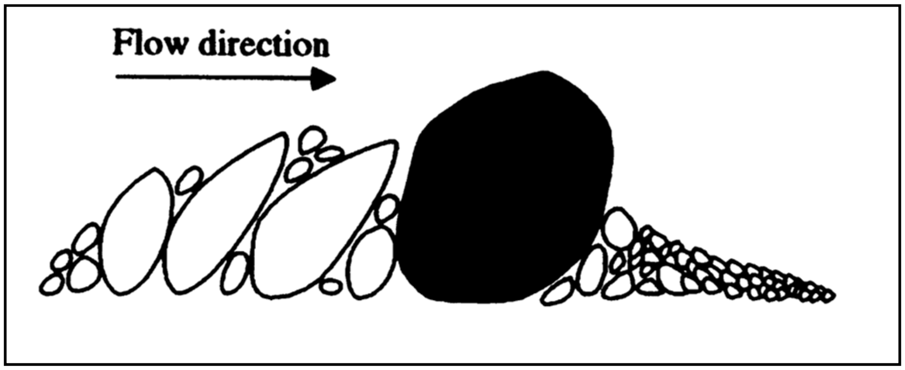
$$\tau = \gamma \cdot R \cdot S$$

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

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

Real stream beds are NOT UNIFORM

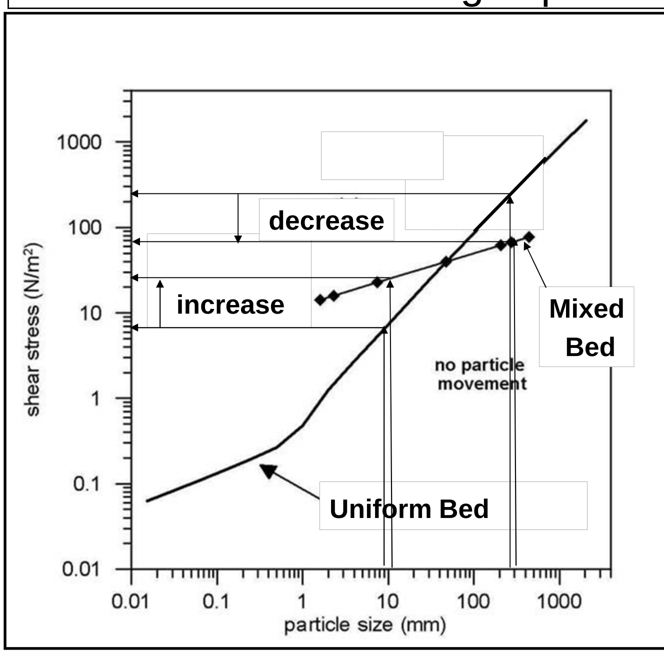
Hiding/exposure for mixed grain sizes



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 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

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

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

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

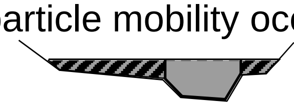
Design application
- Bed mobility
- Bed stability

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

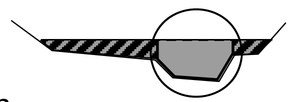
1. Determine flow hydraulics
   - Calculate shear stress and/or unit discharge
   - Active channel
   - Range of discharges: Q_{bf}, $Q_{1.5}$-Q_{100}
2. Calculate critical shear stress and/or unit discharge
   - D_{84} particle size
   - Entire particle size distribution
3. Determine when particle mobility 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

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: Rountree Trib at W Main St

Sediment mobility

(Excel Example – Shear Stress – XS 2 Ref Reach)

Hydraulics												Particle Mobility/Stability					
Recurrence Interval	Discharge, Q (ft^3/s)	Floodplain n value	Channel n value	Channel slope, S_c	Energy slope, S_e	Total flow width, W_t (ft)	Channel flow width, W_c (ft)	Total hydraulic radius, R_t (ft)	Channel Hydraulic Radius, R_c (ft)	Total boundary shear stress, τ_t (lb/ft^2)[a]	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Shield's entrainment 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: XS2																	
	50	0.080	0.040	0.0222	0.0194	25.55	9.99	0.52	0.85	0.63	**1.02**	45	150	42	0.054	**1.18**	no
	60	0.080	0.040	0.0222	0.0200	26.69	10.56	0.58	0.88	0.73	**1.10**	45	150	42	0.054	**1.18**	no
1.5	90	0.080	0.040	0.0222	0.0228	29.24	11.86	0.71	0.96	1.00	**1.36**	45	150	42	0.054	**1.18**	yes
2	110	0.080	0.040	0.0222	0.0225	30.96	12.73	0.79	1.01	1.11	**1.43**	45	150	42	0.054	**1.18**	yes
5	195	0.080	0.040	0.0222	0.0211	46.16	14.30	0.88	1.30	1.16	**1.72**	45	150	42	0.054	**1.18**	yes
10	242	0.080	0.040	0.0222	0.0224	47.92	14.30	0.98	1.43	1.37	**2.00**	45	150	42	0.054	**1.18**	yes
50	390	0.080	0.040	0.0222	0.0211	53.67	14.30	1.27	1.84	1.68	**2.43**	45	150	42	0.054	**1.18**	yes
100	495	0.080	0.040	0.0222	0.0215	56.81	14.30	1.43	2.07	1.92	**2.78**	45	150	42	0.054	**1.18**	yes
500	694	0.080	0.040	0.0222	0.0204	61.25	14.30	1.73	2.49	2.21	**3.16**	45	150	42	0.054	**1.18**	yes
500+	974	0.080	0.040	0.0222	0.0201	65.23	14.30	2.10	2.96	2.63	**3.71**	45	150	42	0.054	**1.18**	yes

D_{84} mobilizes in reference reach between 60 and 90 cfs (~1.5-yr flood)

Sediment Mobility

(Excel Example – Shear Stress – XS 4.5 Middle 20' Wide Conspan Culvert)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (ft)	Chan-nel flow width, W_c (ft)	Total hydraulic radius, R_t (ft)	Channel Hydraulic Radius, R_c (ft)	Total boundary shear stress, τ_t (lb/ft^2)[a]	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	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 stream simulation design channel for 20'x8' Conspan culvert with a channel-bed gradient of 0.0207 (mid culv)																	
	50	0.080	0.040	0.0207	0.0207	11.01	11.01	0.88	0.88	1.14	**1.14**	45	150	42	0.054	**1.18**	no
	60	0.080	0.040	0.0207	0.0207	12.05	12.05	0.93	0.93	1.20	**1.20**	45	150	42	0.054	**1.18**	yes
1.5	90	0.080	0.040	0.0207	0.0206	14.54	14.54	1.06	1.06	1.37	**1.37**	45	150	42	0.054	**1.18**	yes
2	110	0.080	0.040	0.0207	0.0207	20.00	15.00	0.91	1.18	1.17	**1.52**	45	150	42	0.054	**1.18**	yes
5	195	0.080	0.040	0.0207	0.0191	20.00	15.00	1.34	1.67	1.60	**2.00**	45	150	42	0.054	**1.18**	yes
10	242	0.080	0.040	0.0207	0.0186	20.00	15.00	1.53	1.91	1.77	**2.22**	45	150	42	0.054	**1.18**	yes
50	390	0.080	0.040	0.0207	0.0177	19.99	15.00	2.01	2.56	2.23	**2.83**	45	150	42	0.054	**1.18**	yes
100	495	0.080	0.040	0.0207	0.0172	19.99	15.00	2.29	2.97	2.46	**3.19**	45	150	42	0.054	**1.18**	yes
500	694	0.080	0.040	0.0207	0.0164	19.99	15.00	2.73	3.68	2.80	**3.77**	45	150	42	0.054	**1.18**	yes
500+	974	0.080	0.040	0.0207	0.0155	19.98	15.00	3.22	4.58	3.12	**4.44**	45	150	42	0.054	**1.18**	yes

D_{84} mobilizes in middle of culvert between 50 and 60 cfs
(<1.5-yr flood)

Sediment mobility

(Excel Example – Shear Stress – XS 4.5 Middle 16' Wide Box Culvert)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (ft)	Chan-nel flow width, W_c (ft)	Total hydraulic radius, R_t (ft)	Channel Hydraulic Radius, R_c (ft)	Total boundary shear stress, τ_t (lb/ft^2)[a]	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	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)
C. Adjusted stream simulation design channel for 20'x8' Conspan culvert with a channel-bed gradient of 0.0207 (mid culv)																	
	50	0.080	0.040	0.0207	0.0207	11.01	11.01	0.88	0.88	1.14	**1.14**	50	165	41	0.052	**1.25**	no
	60	0.080	0.040	0.0207	0.0207	12.05	12.05	0.93	0.93	1.20	**1.20**	50	165	41	0.052	**1.25**	no
1.5	90	0.080	0.040	0.0207	0.0206	14.54	14.54	1.06	1.06	1.37	**1.37**	50	165	41	0.052	**1.25**	yes
2	110	0.080	0.040	0.0207	0.0207	20.00	15.00	0.91	1.18	1.17	**1.52**	50	165	41	0.052	**1.25**	yes
5	195	0.080	0.040	0.0207	0.0191	20.00	15.00	1.34	1.67	1.60	**2.00**	50	165	41	0.052	**1.25**	yes
10	242	0.080	0.040	0.0207	0.0186	20.00	15.00	1.53	1.91	1.77	**2.22**	50	165	41	0.052	**1.25**	yes
50	390	0.080	0.040	0.0207	0.0177	19.99	15.00	2.01	2.56	2.23	**2.83**	50	165	41	0.052	**1.25**	yes
100	495	0.080	0.040	0.0207	0.0172	19.99	15.00	2.29	2.97	2.46	**3.19**	50	165	41	0.052	**1.25**	yes
500	694	0.080	0.040	0.0207	0.0164	19.99	15.00	2.73	3.68	2.80	**3.77**	50	165	41	0.052	**1.25**	yes
500+	974	0.080	0.040	0.0207	0.0155	19.98	15.00	3.22	4.58	3.12	**4.44**	50	165	41	0.052	**1.25**	yes

With 10% increase in bed material size,
D_{84} mobilizes in middle of culvert between 60 and 90 cfs
(~1.5-yr flood)

Sediment mobility

(Excel Ex – Shear Stress – 20’ Conspan Culvert Adjustment +10%)

Ref Reach (XS2): D_{84} mobile at 55 cfs (<$Q_{1.5}$)
Initial Bed: D_{84} mobile at 75 cfs (~$Q_{1.5}$)
Adjusted Bed: D_{84} mobile at 75 cfs (~$Q_{1.5}$)

D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Description
45	150	42	initial reference reach particle size
49.5	165.0	42	adjusted particle sizes in design channel
		10	**percent particle size adjustment**

Sediment stability

(Excel Example – Shear Stress – XS 2 Ref Reach)

Hydraulics												Particle Mobility/Stability					
Recur-rence Interval	Dis-charge, Q (ft^3/s)	Flood-plain n value	Chan-nel n value	Chan-nel slope, S_c	Energy slope, S_e	Total flow width, W_t (ft)	Chan-nel flow width, W_c (ft)	Total hydraulic radius, R_t (ft)	Channel Hydraulic Radius, R_c (ft)	Total boundary shear stress, τ_t (lb/ft^2)[a]	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Shield's entrain-ment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, τ_{c-D84} (lb/ft^2)[d]**	D_{84} Particle Stable (yes/no)
A. Reference reach cross section: XS2																	
	50.0	0.080	0.040	0.0222	0.0194	25.55	9.99	0.52	0.85	0.63	**1.02**	474	528	42	0.054	**8.93**	yes
	60.0	0.080	0.040	0.0222	0.0200	26.69	10.56	0.58	0.88	0.73	**1.10**	474	528	42	0.054	**8.93**	yes
1.5	90.0	0.080	0.040	0.0222	0.0228	29.24	11.86	0.71	0.96	1.00	**1.36**	474	528	42	0.054	**8.93**	yes
2	110.0	0.080	0.040	0.0222	0.0225	30.96	12.73	0.79	1.01	1.11	**1.43**	474	528	42	0.054	**8.93**	yes
5	195.0	0.080	0.040	0.0222	0.0211	46.16	14.30	0.88	1.30	1.16	**1.72**	474	528	42	0.054	**8.93**	yes
10	242.0	0.080	0.040	0.0222	0.0224	47.92	14.30	0.98	1.43	1.37	**2.00**	474	528	42	0.054	**8.93**	yes
50	390.0	0.080	0.040	0.0222	0.0211	53.67	14.30	1.27	1.84	1.68	**2.43**	474	528	42	0.054	**8.93**	yes
100	495.0	0.080	0.040	0.0222	0.0215	56.81	14.30	1.43	2.07	1.92	**2.78**	474	528	42	0.054	**8.93**	yes
500	694.0	0.080	0.040	0.0222	0.0204	61.25	14.30	1.73	2.49	2.21	**3.16**	474	528	42	0.054	**8.93**	yes
500+	974.0	0.080	0.040	0.0222	0.0201	65.23	14.30	2.10	2.96	2.63	**3.71**	474	528	42	0.054	**8.93**	yes

D_{84} (21 inches or 528 mm) for key pieces stable at all flows.

Sediment stability

(Excel Example – Shear Stress – XS 4.5 16’ Box Culvert)

Hydraulics												Particle Mobility/Stability					
Recurrence Interval	Discharge, Q (ft^3/s)	Floodplain n value	Channel n value	Channel slope, S_c	Energy slope, S_e	Total flow width, W_t (ft)	Channel flow width, W_c (ft)	Total hydraulic radius, R_t (ft)	Channel Hydraulic Radius, R_c (ft)	Total boundary shear stress, τ_t (lb/ft^2)[a]	**Channel boundary shear stress, τ_c (lb/ft^2)[b]**	D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Shield's entrainment for τ^*_{D50} [c]	**Critical Shear Stress to Entrain D_{84} Particle Size, $\tau_{c\text{-}D84}$ (lb/ft^2)[d]**	D_{84} Particle Stable (yes/no)
B. Preliminary stream simulation design channel for 20'x8' Conspan culvert with a channel-bed gradient of 0.0207 (mid culv)																	
	50.0	0.080	0.040	0.0207	0.0207	11.01	11.01	0.88	0.88	1.14	**1.14**	474	528	42	0.054	**8.93**	yes
	60.0	0.080	0.040	0.0207	0.0207	12.05	12.05	0.93	0.93	1.20	**1.20**	474	528	42	0.054	**8.93**	yes
1.5	90.0	0.080	0.040	0.0207	0.0206	14.54	14.54	1.06	1.06	1.37	**1.37**	474	528	42	0.054	**8.93**	yes
2	110.0	0.080	0.040	0.0207	0.0207	20.00	15.00	0.91	1.18	1.17	**1.52**	474	528	42	0.054	**8.93**	yes
5	195.0	0.080	0.040	0.0207	0.0191	20.00	15.00	1.34	1.67	1.60	**2.00**	474	528	42	0.054	**8.93**	yes
10	242.0	0.080	0.040	0.0207	0.0186	20.00	15.00	1.53	1.91	1.77	**2.22**	474	528	42	0.054	**8.93**	yes
50	390.0	0.080	0.040	0.0207	0.0177	19.99	15.00	2.01	2.56	2.23	**2.83**	474	528	42	0.054	**8.93**	yes
100	495.0	0.080	0.040	0.0207	0.0172	19.99	15.00	2.29	2.97	2.46	**3.19**	474	528	42	0.054	**8.93**	yes
500	694.0	0.080	0.040	0.0207	0.0164	19.99	15.00	2.73	3.68	2.80	**3.77**	474	528	42	0.054	**8.93**	yes
500+	974.0	0.080	0.040	0.0207	0.0155	19.98	15.00	3.22	4.58	3.12	**4.44**	474	528	42	0.054	**8.93**	yes

D_{84} (21 inches or 528 mm) for key pieces stable at all flows.