Culvert Design Process

Hydrology

↓

Site Assessment

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Alignment and Profile

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Bed and Banks

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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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- Bed stability

Prevent bed failure

Note regrade

Original profile

Resulting profile

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

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- Bed stability

Factors affecting motion

Resisting Factors:

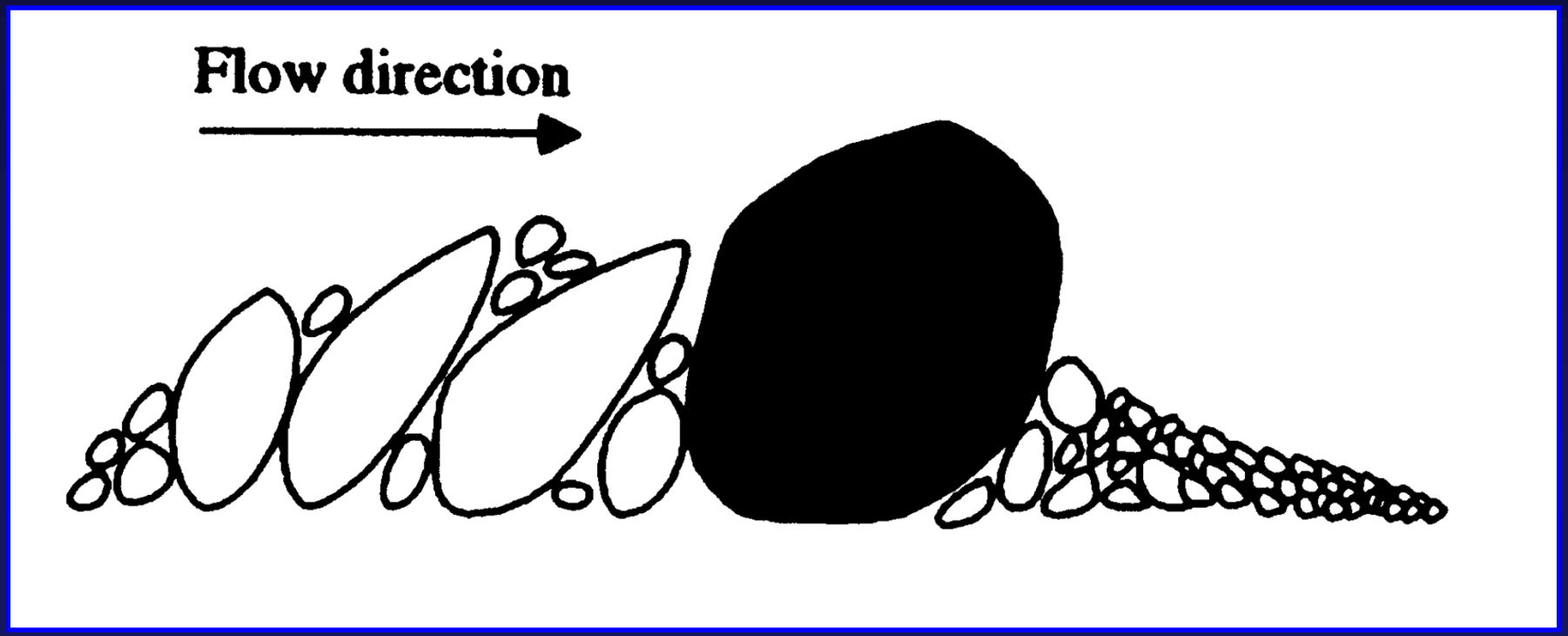
- particle size
- particle shape
- particle density
- pivot angle

Resisting Factors:

1-b - packing of particles
- orientation of particles
- sorting of sediments
- distribution of bedforms
- exposure to flow

Driving Forces:

- velocity
- flow depth
- slope
- turbulence



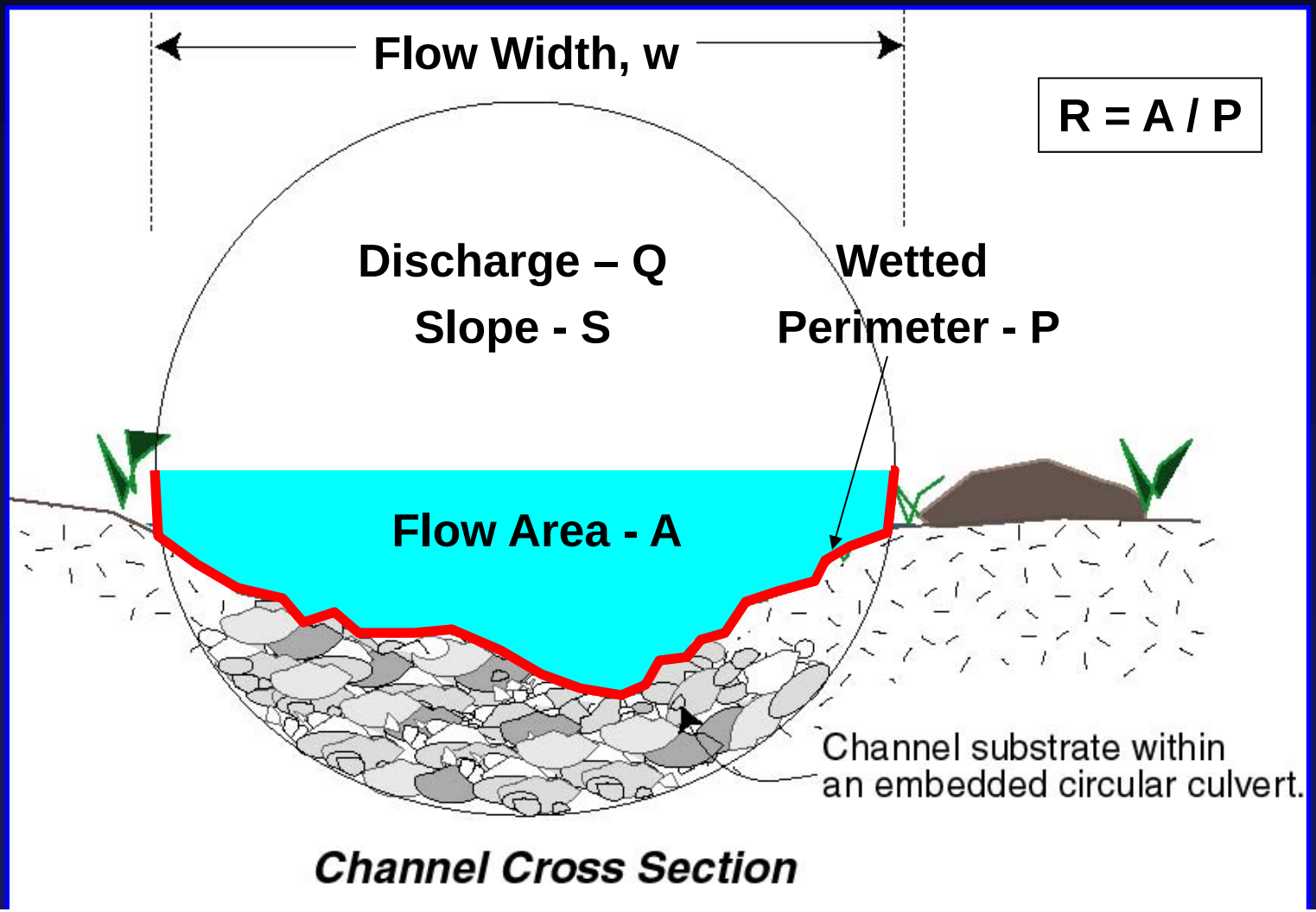
Quantifying hydrodynamic forces

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

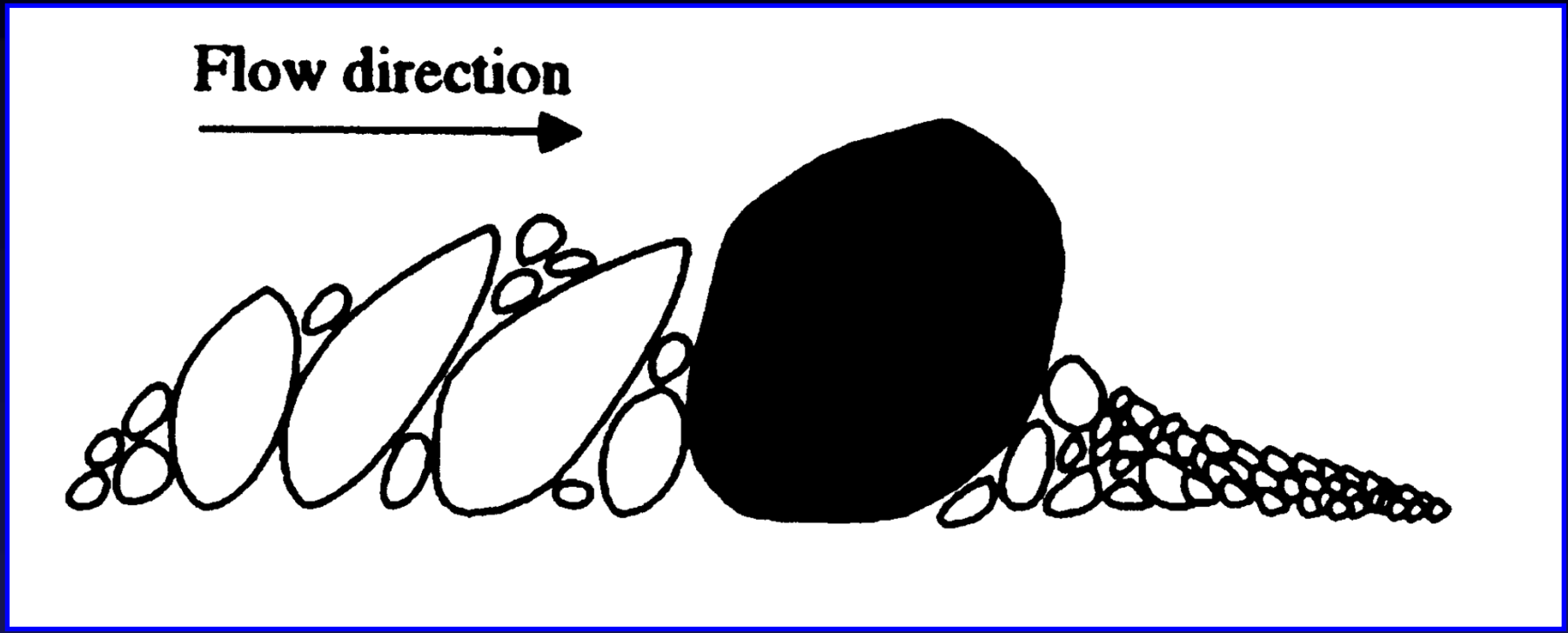
$$\tau = \gamma \cdot R \cdot S$$

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

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

Real stream beds are NOT UNIFORM

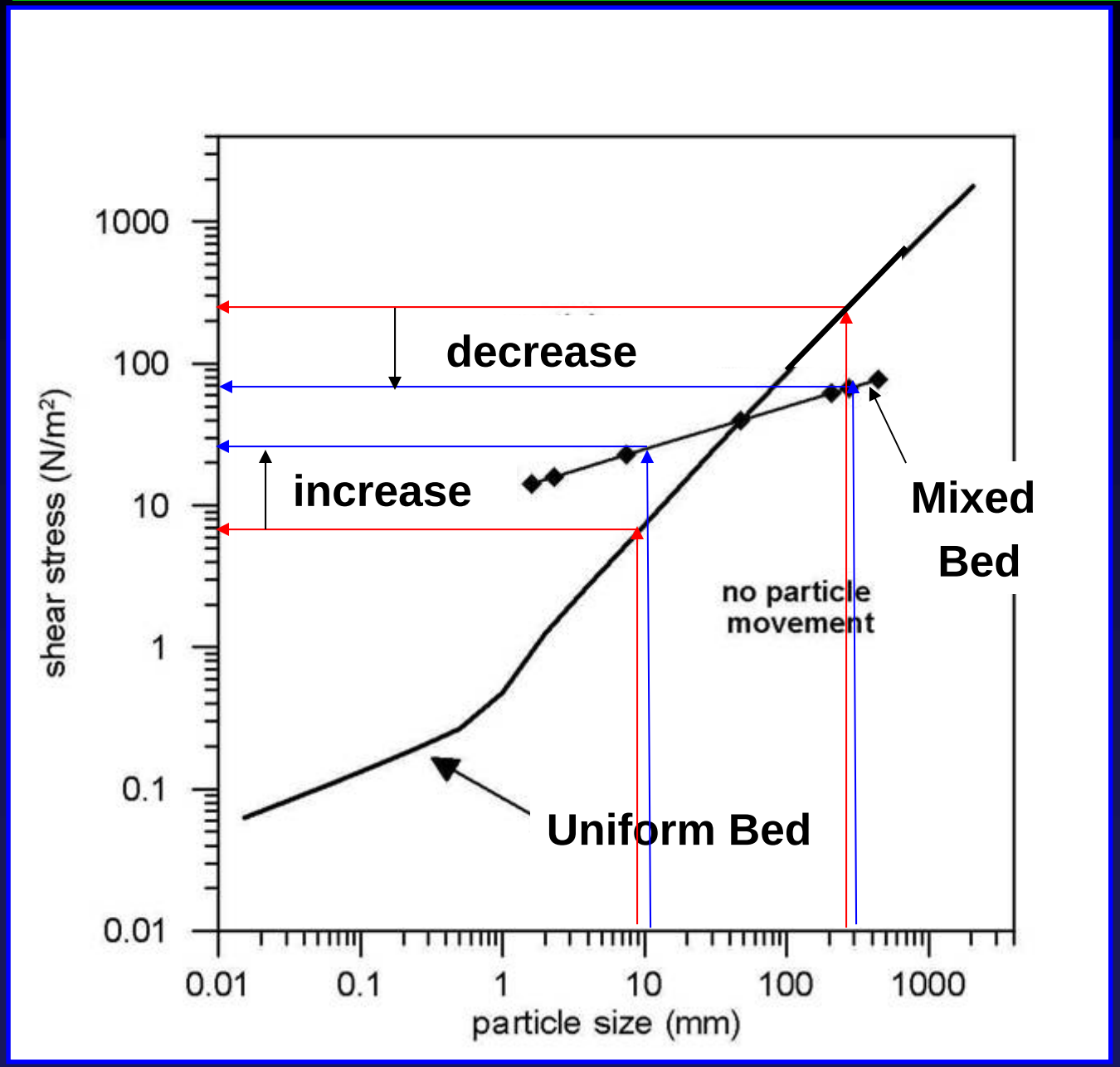
Hiding/exposure for mixed grain sizes



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%, Di/D50 ratios < 25, and R/D84 > 5 (R/D50 >10)

Critical unit discharge
Bathurst (1987)

Resisting force

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

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

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

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/D84 < 5 and R/D50 <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

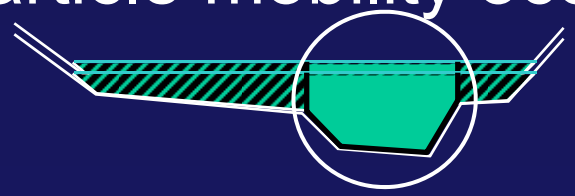
- Compares design channel bed to reference reach
- D_{84} particle sizes should mobilize at the same flow in both channels
- Channel roughness, channel form, and bed mobility are controlled by D_{84} particles sizes
- Comparative analysis based on reference reach calibrates the model; therefore analysis 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: Trout Trib at Cty U

Sediment mobility

(Excel Example – Shear Stress – XS 1 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, $\tau_{c\text{-}D84}$ (lb/ft^2) [d]**	D_{84} Particle Mobile (yes/no)
A. Reference reach cross section: XS1 (farthest downstream from proposed box culvert)																	
	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	0.100	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	0.100	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	0.100	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	0.0114	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	0.0114	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	0.0114	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	0.0114	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	0.0114	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)

Sediment Mobility

(Excel Example – Shear Stress – XS 3b 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 $\tau^*_{D50}{}^c$	**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 16 ft wide box culvert structure with a channel-bed gradient of 1.1% (XS3b)																	
	20	0.010	0.040	0.0110	0.0133	11.59	11.59	0.57	0.57	0.47	**0.47**	35	80	41	0.052	**0.79**	no
	25	0.010	0.040	0.0110	0.0122	12.01	12.01	0.66	0.66	0.50	**0.50**	35	80	41	0.052	**0.79**	no
1.5	30	0.010	0.040	0.0110	0.0113	12.21	12.21	0.74	0.74	0.52	**0.52**	35	80	41	0.052	**0.79**	no
2	40	0.010	0.040	0.0110	0.0102	12.58	12.58	0.88	0.88	0.56	**0.56**	35	80	41	0.052	**0.79**	no
5	67	0.010	0.040	0.0110	0.0089	13.42	13.42	1.19	1.19	0.66	**0.66**	35	80	41	0.052	**0.79**	no
10	85	0.010	0.040	0.0110	0.0088	13.86	13.86	1.34	1.34	0.74	**0.74**	35	80	41	0.052	**0.79**	no
25	106	0.010	0.040	0.0110	0.0086	16.00	14.00	1.35	1.53	0.72	**0.82**	35	80	41	0.052	**0.79**	yes
50	121	0.010	0.040	0.0110	0.0088	16.00	14.00	1.44	1.64	0.79	**0.90**	35	80	41	0.052	**0.79**	yes
100	136	0.010	0.040	0.0110	0.0093	16.00	14.00	1.51	1.73	0.87	**1.01**	35	80	41	0.052	**0.79**	yes
500	166	0.010	0.040	0.0110	0.0101	16.00	14.00	1.64	1.90	1.03	**1.20**	35	80	41	0.052	**0.79**	yes

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)

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 simulation design channel (+25%) for 16 ft wide box culvert structure with a channel-bed gradient of 1.1% (XS3b)																	
	20	0.010	0.040	0.0110	0.0133	11.59	11.59	0.57	0.57	0.47	**0.47**	44	100	40	0.050	**0.95**	no
	25	0.010	0.040	0.0110	0.0122	12.01	12.01	0.66	0.66	0.50	**0.50**	44	100	40	0.050	**0.95**	no
1.5	30	0.010	0.040	0.0110	0.0113	12.21	12.21	0.74	0.74	0.52	**0.52**	44	100	40	0.050	**0.95**	no
2	40	0.010	0.040	0.0110	0.0102	12.58	12.58	0.88	0.88	0.56	**0.56**	44	100	40	0.050	**0.95**	no
5	67	0.010	0.040	0.0110	0.0089	13.42	13.42	1.19	1.19	0.66	**0.66**	44	100	40	0.050	**0.95**	no
10	85	0.010	0.040	0.0110	0.0088	13.86	13.86	1.34	1.34	0.74	**0.74**	44	100	40	0.050	**0.95**	no
25	106	0.010	0.040	0.0110	0.0086	16.00	14.00	1.35	1.53	0.72	**0.82**	44	100	40	0.050	**0.95**	no
50	121	0.010	0.040	0.0110	0.0088	16.00	14.00	1.44	1.64	0.79	**0.90**	44	100	40	0.050	**0.95**	no
100	136	0.010	0.040	0.0110	0.0093	16.00	14.00	1.51	1.73	0.87	**1.01**	44	100	40	0.050	**0.95**	yes
500	166	0.010	0.040	0.0110	0.0101	16.00	14.00	1.64	1.90	1.03	**1.20**	44	100	40	0.050	**0.95**	yes

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

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})

D_{50} (mm)	D_{84} (mm)	Angle of repose ϕ	Description
35	80	41	initial reference reach particle size
43.8	100.0	40	adjusted particle sizes in design channel
		25	**percent particle size adjustment**

Sediment stability

(Excel Example – Shear Stress – XS 1 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, $\tau_{c\text{-}D84}$ (lb/ft^2) [d]**	D_{84} Particle Stable (yes/no)
A. Reference reach cross section (key pieces): XS1 (farthest downstream, incised, good gradient match)																	
	20	0.100	0.040	0.0110	0.0114	15.01	15.01	0.59	0.59	0.42	**0.42**	203	305	42	0.054	**4.18**	yes
	25	0.100	0.040	0.0110	0.0114	15.35	15.35	0.66	0.66	0.47	**0.47**	203	305	42	0.054	**4.18**	yes
1.5	30	0.100	0.040	0.0110	0.0114	15.63	15.63	0.73	0.73	0.52	**0.52**	203	305	42	0.054	**4.18**	yes
2	40	0.100	0.040	0.0110	0.0114	16.14	16.14	0.85	0.85	0.60	**0.60**	203	305	42	0.054	**4.18**	yes
5	67	0.100	0.040	0.0110	0.0114	17.29	17.29	1.10	1.10	0.79	**0.79**	203	305	42	0.054	**4.18**	yes
10	85	0.100	0.040	0.0110	0.0114	17.95	17.95	1.24	1.24	0.88	**0.88**	203	305	42	0.054	**4.18**	yes
25	106	0.100	0.040	0.0110	0.0114	23.73	18.64	1.10	1.38	0.78	**0.98**	203	305	42	0.054	**4.18**	yes
50	121	0.100	0.040	0.0110	0.0114	35.23	18.96	0.85	1.47	0.61	**1.05**	203	305	42	0.054	**4.18**	yes
100	136	0.100	0.040	0.0110	0.0114	53.59	19.22	0.65	1.56	0.46	**1.11**	203	305	42	0.054	**4.18**	yes
500	166	0.100	0.040	0.0096	0.0114	75.32	19.64	0.62	1.68	0.44	**1.20**	203	305	42	0.054	**4.18**	yes

D_{84} (12 inches or 305 mm) for key pieces stable at all flows.

Sediment stability

(Excel Example – Shear Stress – XS 3b 16' 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 Stable (yes/no)
B. Preliminary stream simulation design channel (key pieces) for 16 ft wide box culvert.																	
	20	0.010	0.040	0.0110	0.0133	11.59	11.59	0.57	0.57	0.47	**0.47**	203	305	42	0.054	**4.18**	yes
	25	0.010	0.040	0.0110	0.0122	12.01	12.01	0.66	0.66	0.50	**0.50**	203	305	42	0.054	**4.18**	yes
1.5	30	0.010	0.040	0.0110	0.0113	12.21	12.21	0.74	0.74	0.52	**0.52**	203	305	42	0.054	**4.18**	yes
2	40	0.010	0.040	0.0110	0.0102	12.58	12.58	0.88	0.88	0.56	**0.56**	203	305	42	0.054	**4.18**	yes
5	67	0.010	0.040	0.0110	0.0089	13.42	13.42	1.19	1.19	0.66	**0.66**	203	305	42	0.054	**4.18**	yes
10	85	0.010	0.040	0.0110	0.0088	13.86	13.86	1.34	1.34	0.74	**0.74**	203	305	42	0.054	**4.18**	yes
25	106	0.010	0.040	0.0110	0.0086	16.00	14.00	1.35	1.53	0.72	**0.82**	203	305	42	0.054	**4.18**	yes
50	121	0.010	0.040	0.0110	0.0088	16.00	14.00	1.44	1.64	0.79	**0.90**	203	305	42	0.054	**4.18**	yes
100	136	0.010	0.040	0.0110	0.0093	16.00	14.00	1.51	1.73	0.87	**1.01**	203	305	42	0.054	**4.18**	yes
500	166	0.010	0.040	0.0110	0.0101	16.00	14.00	1.64	1.90	1.03	**1.20**	203	305	42	0.054	**4.18**	yes

D_{84} (12 inches or 305 mm) for key pieces stable at all flows.