Hydraulics 101 – Part II

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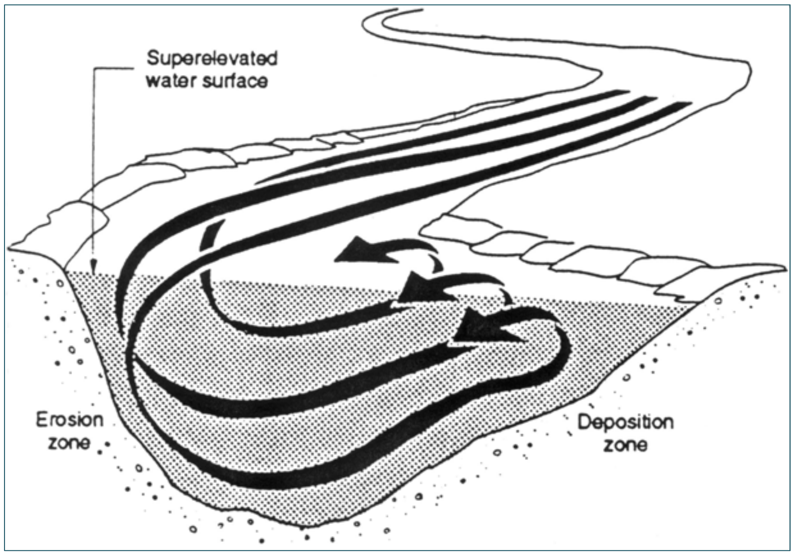
ASCE | KNOWLEDGE & LEARNING

Course Outline, Part II

- Shear Stress at Bends
- Bridge Hydraulics and Scour
- Culverts
- Weirs
- Channel Stability
- Grade Control

2

Bend Scour and Shear Stress

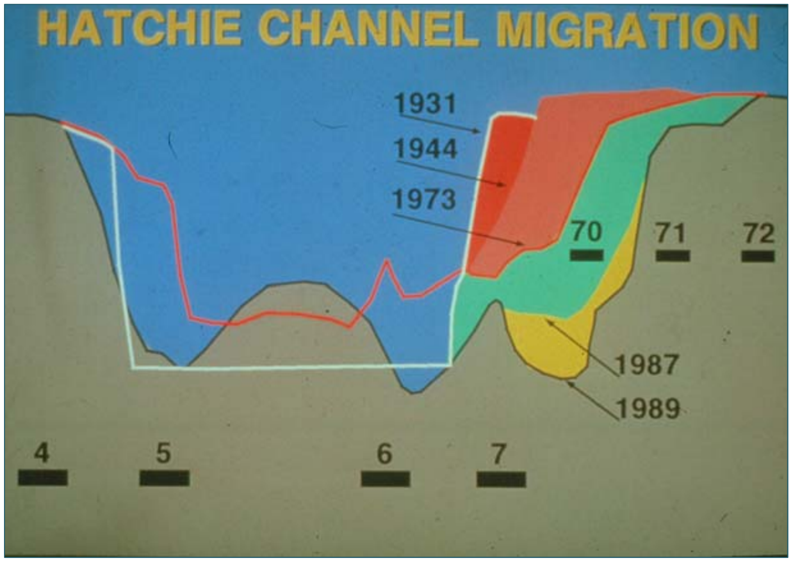


3

Channel Bend Shear Stress and Scour

4

Bend Scour



Shear Stress in a Bend

$\tau_b = K\gamma_w RS_f$

$K = 2.5(R_c/W)^{-0.321}$

Where:

τ_b = shear stress at the outside of a bend

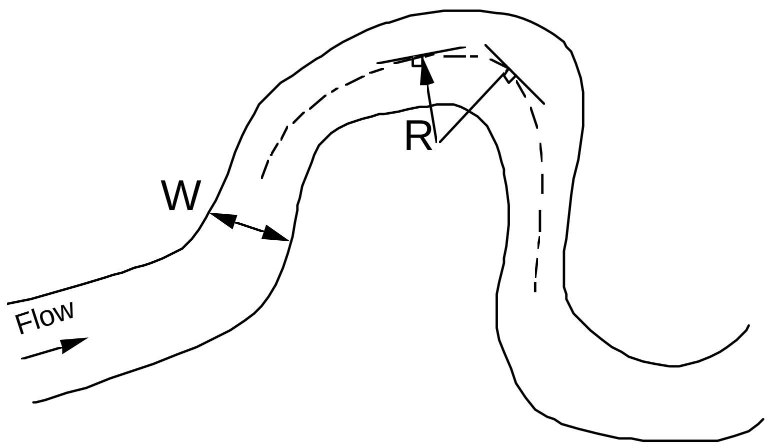
R = hydraulic radius

K = coefficient for bend shear stress related to R_c/W

R_c = bend curvature (radius of the bend)

W = top width of the channel

Determining Bend Radius



Draw tangents to river centerline along curve, make perpendicular lines from the tangents, find intersection closest to the centerline, and average the lengths of the two perpendicular lines

7

Example 3

- The TRM bare soil covered channel from example 2 in Part 1 is to go around a bend with a radius of curvature of 50 feet. Will the TRM be able to handle the additional shear stress on the outside?
  - From the hydraulic calculations, the top width of the water was 18.0 feet so therefore $R_c/W = 50/18 = 2.8$
  - The adjustment factor for bends is $K = 2.5(R_c/W)^{-0.321} = 2.5(2.8)^{-0.321} = 1.8$
  - From example 2, $\tau_o = 2.93$ lb/ft^2 therefore $\tau_b = 2.93 \times 1.8 = 5.27$ lb/ft^2
  - NAG 550 had been selected and its allowable shear stress was 3.25 lb/ft^2
  - The TRM will not work, so need to go up to at least Pro/Enka II = 10 lb/ft^2 (see next slide)

8

Example 3, continued

Dotted red line was selected for straight channel for velocity of 10.4 ft/s and shear stress = 2.93 lbs/ft^2 (C350 was too close)

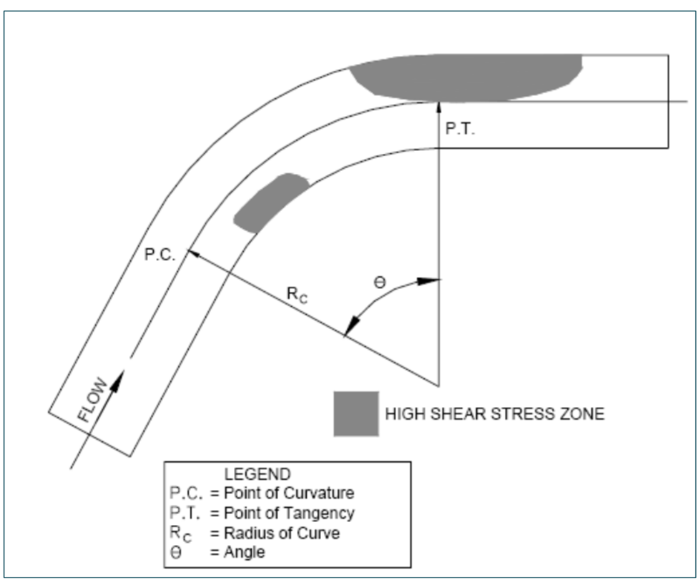
Solid red line is selected for outside of curve at shear stress = 5.27 lb/ft^2

Turf Reinforced Mats (TRM)

TRM	v_{max} (ft/s)	t_{all} (lbs/ft^2)
NAG, SC250; bare soil	9.5	2.50
NAG, C350; bare soil	10.5	3.00
NAG, P550; bare soil	12.5	3.25
Pro/Enka II; bare soil	13.0	10.0
Pro/Enka, 7220, BFM, vegetated	14.0	8.0
NAG, C350; vegetated	20.0	10.0
NAG, P550; vegetated	25.0	12.5

9

Longitudinal Bend Shear Extents



10

Bend Shear Stress Extents

(Rozovskii, adopted by Clark Co., NV)

$$X = 2.3 (C / g^{1/2}) Y = (0.6 Y^{1.17})/n$$

Where:

X = distance from end of channel curvature (PT) to downstream point at which secondary currents have dissipated, (ft)

C = Chezy coefficient = $(1.486/n) R^{1/6}$

g = gravitational acceleration, (32.2 ft/s^2)

y = depth of flow - use maximum flow depth, exclusive of bend scour, within bend, (ft)

n = Manning's roughness coefficient

Bend Shear Stress Extents

- A conservative estimate of longitudinal extent of the extra shear stress due to the bend, both upstream and downstream of the curve, is to assume it extends:
  - a distance X upstream of point of curvature (P.C.), and
  - a minimum of 2 times X downstream of point of tangency (P.T.)
- Do not forget that the bend causes the water surface elevation to rise on the outside of the bend, so any protection should extend high enough to account for this.

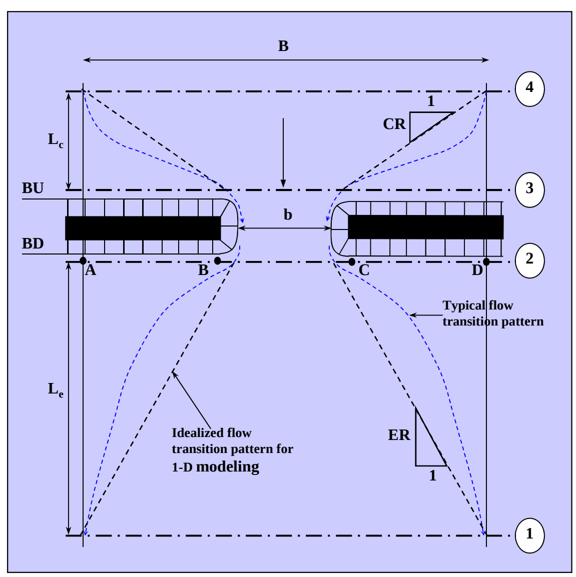
Example 4

- From example 3, what are the longitudinal extents that the bank protection should be placed?
  - From the hydraulic calculations, the flow depth, Y, was 2.35 ft.
  - For n = 0.025 and extent = X = 2.3 $(C / g^{1/2})$ Y = $(0.6\ Y^{1.17})/n$
  - = $(0.6 \times 2.35^{1.17})/0.025$ = 65 ft.
  - From recommendations using previous slide, install protection 65 feet upstream of the point of curvature (P.C.) and 2 x 65 = 130 feet downstream of the point of tangency (P.T.).
  - Don't forget to vertically extend the outside of the bend to account for super elevation.

13

Bridge Hydraulics

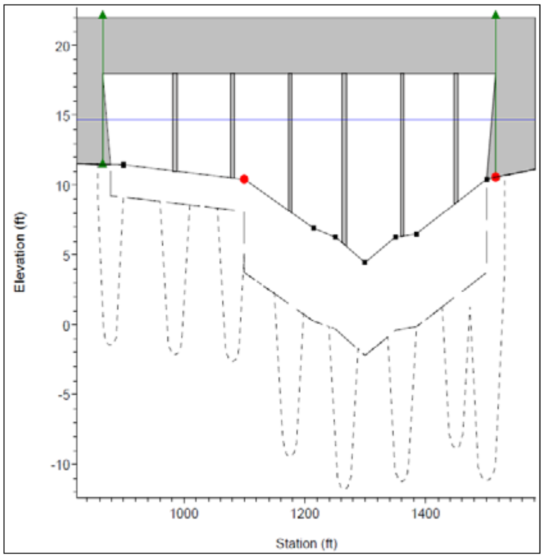
- Section 4 to 3: contraction zone
- Section 3 to 2: between abutments
- Section 2 to 1: expansion zone
- CR is contraction ratio
- ER is expansion ratio



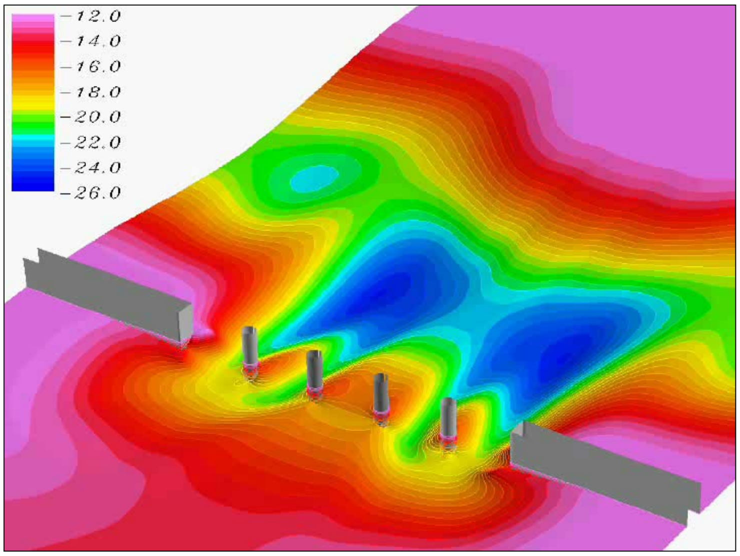
14

Bridge Scour Considerations

- Contraction Scour
- Channel Scour/Degradation
- Abutment Scour
  - o Shape of abutment
  - o Amount of water captured in O/B
- Pier Scour
  - o Size
  - o Water angle of attack
- Debris Build-up
- Bed Forms (e.g., dunes)



Contraction Scour



Degradation

17

Abutment Scour

18

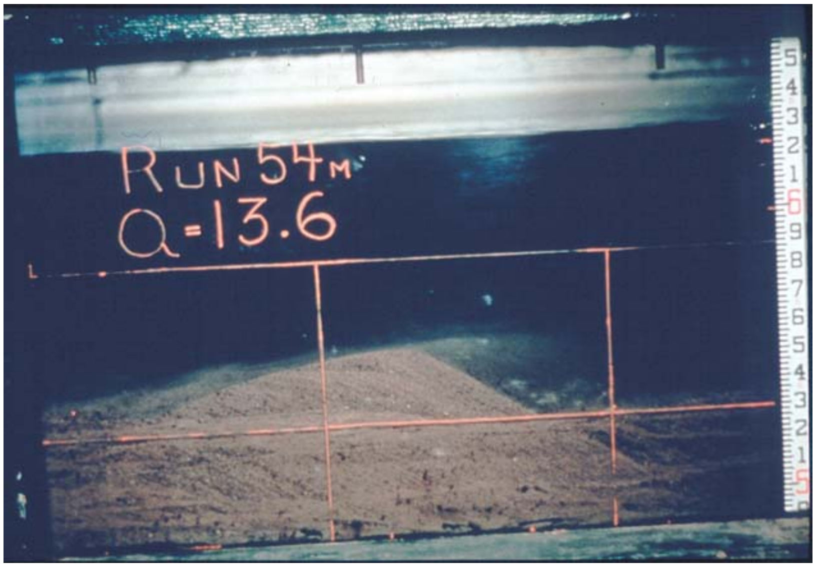
Pier Scour

19

Debris Accumulation – Affects Pier Width

20

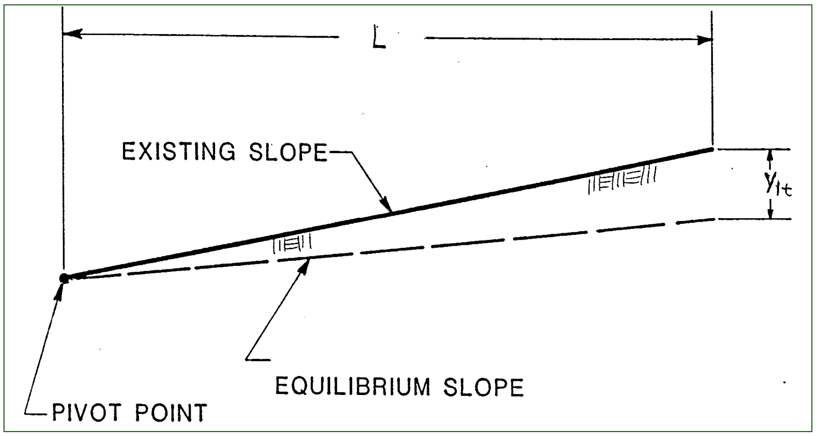
Bed Forms



Bed Forms

Long-term Degradation

Scour depth due to long term degradation is the difference between existing slope and the long term equilibrium slope at a given location upstream from a stable "pivot" point.



23

Long-term Degradation

$$y_{lt} = (S_0 - S_L)\,L$$

Where:

y_{lt} = long term degradation, (ft)

S_0 = existing channel slope, (ft/ft)

S_L = equilibrium slope, (ft/ft)

L = distance between downstream control point and point of interest, (ft)

24

Design Considerations for Scour

- Scour analysis is required for design and evaluation of channels and hydraulic structures such as bank protection, bridges, culverts, grade-control structures and utilities.

- The scour components to be considered will depend on the structures present, the bed material, presence of bends, etc.

25

Design Considerations for Scour

- Factors to be considered in determining scour depths include:
  - Long-term degradation and aggradation, general scour, and local scour at structures that affect flow.
  - For sand bed streams, bed forms.
  - Bend scour if bends are present - the increased water surface elevation due to super elevation must be taken into consideration.
  - Ensure aggradation has not caused an increase in water surface elevation and thus freeboard.

26

Design Considerations

- Factors to be considered (cont.):
  - For bank protection projects with bridge crossing, check proximity of piers to bank protection toe-down.
  - Toe-down on upstream side of grade-control structures must be toed-in to prevent undermining on upstream side.
  - Maximum total scour can occur at any point in a cross section.
  - For pipeline crossings, lateral migration estimates are required to establish lateral extent of buried pipe.
  - Some scour equations may include an estimate for more than one scour component. Understand the results.

27

Determination of Total Scour

- Total scour is the sum of all scour components that apply to study site:
  - Long-term degradation
  - General scour (design flood event)
  - Local scour (e.g., pier, abutment, impinging flow)
  - Bend scour
  - Bed form scour
  - Low-flow channel incisement

$$y_{ts} = y_{lt} + y_{gs} + y_{ls} + y_{bs} + y_{bf} + y_{lf}$$

28

Weirs

- Generally goes completely across stream
- Used to create recreational and water supply reservoirs
- Orientation is perpendicular to flow

29

Weirs

$$Q = C L H^{3/2}$$

Q - The total flow over the weir

C - Coefficient of discharge for weir flow, value depends on unit system and type of weir crest (sharp or broad)

L - Effective length of the weir

H - Height of water above the top of weir elevation

30

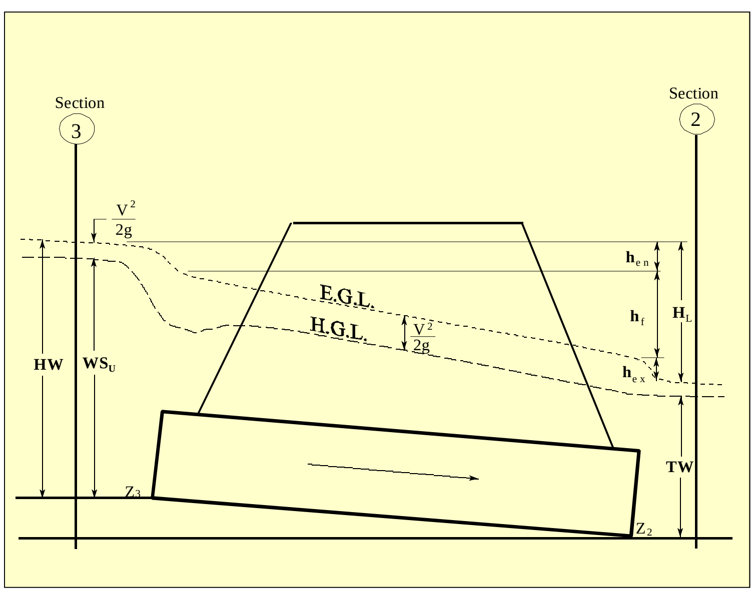
Culverts: General Information

Culverts are made up of:

- An **entrance** where water flows into the culvert
- A **barrel**, which is the closed conduit portion of the culvert
- An **exit**, where the water flows out of the culvert

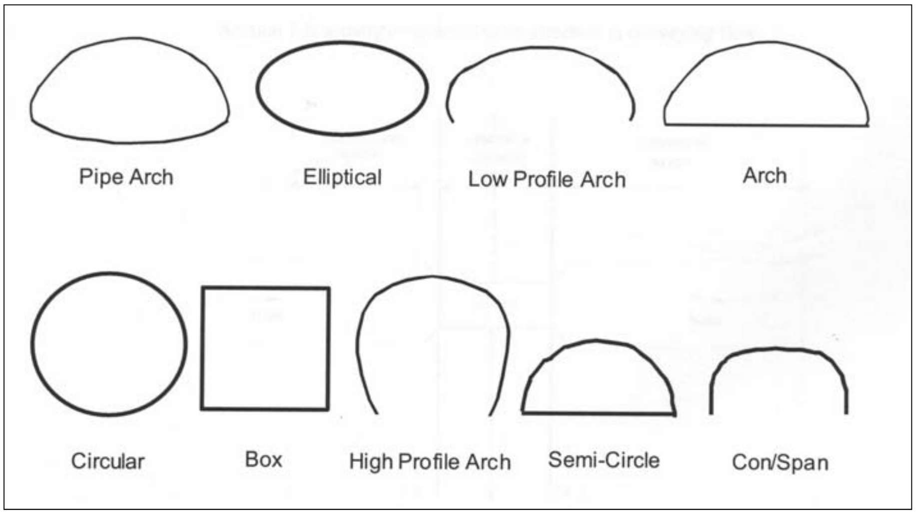
31

Hydraulic Features of a Culvert



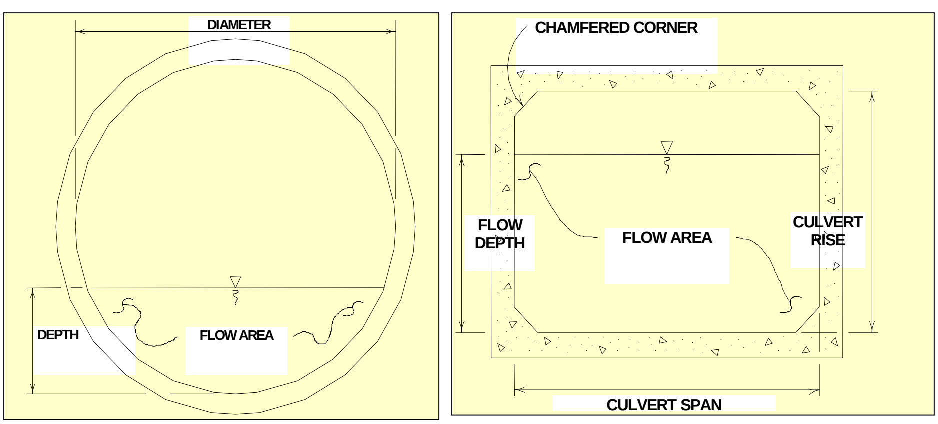
32

Typical Shapes of Culverts



33

Introduction to Culvert Terminology



34

Introduction to Culvert Terminology

- The total flow capacity of a culvert depends upon the characteristics of the entrance as well as the culvert barrel and exit.
- The **tailwater** (TW) at a culvert is the depth of water on the exit or downstream side of the culvert, as measured from the downstream invert of the culvert.
- The tailwater depth depends on the flow rate and hydraulic conditions downstream of the culvert.
- The **invert** is the lowest point on the inside of the culvert at a particular cross section.

35

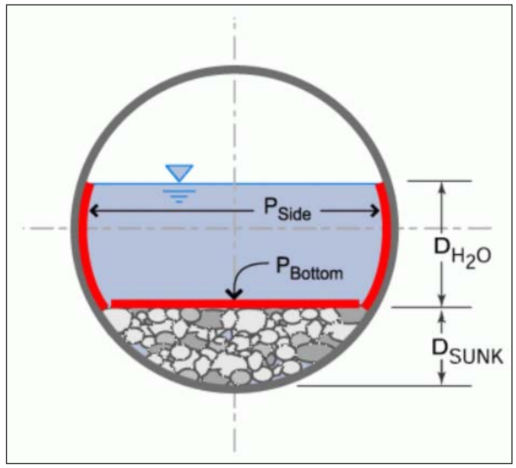
Introduction to Culvert Terminology

- The **Headwater** (HW) is the depth from the culvert inlet invert to the energy grade line for the cross section just upstream of the culvert.
- The **Total Energy** at any location is equal to the elevation of the invert plus the specific energy (depth of water + velocity head) at that location.
- The upstream water surface (WS_U) is obtained by placing that energy into the upstream cross section and computing the water surface that corresponds to that energy for the given flow rate.

36

Multiple Manning n inside of Culvert and Partially Filled or Buried Culverts

- Natural stream bottoms
- Different n values due to low flows
- Something placed in the bottom of the culvert for fish passage
- Uses composite n analyses



37

Flow Analysis for Culverts – Inlet Control

- The analysis of flow in culverts is quite complicated; therefore it is common to use the concepts of "inlet control" and "outlet control" to simplify the analysis.
- **Inlet control** *(How much energy is required to push the Q into the culvert?)*
  - This occurs when the flow capacity of the culvert entrance is less than the capacity of the culvert barrel – which is the usual case for design flood flows.

38

Flow Analysis for Culverts – Outlet Control

Outlet Control (*How much energy is required to push the water through and out of the barrel?)*

- Occurs when the culvert flow capacity is limited by downstream conditions (high tailwater) and/or by the flow carrying capacity of the culvert barrel.
- Usually occurs when there is a high tailwater or the culvert is unusually long.
- If caused by high tailwater, you cannot improve the design because the problem is caused by downstream conditions.
- The highest of the two energies "controls" and is used to calculate the HW elevation (water elevation just upstream of the culvert).

Flow Analysis for Culverts

Table 1--Factors Influencing Culvert Performance.

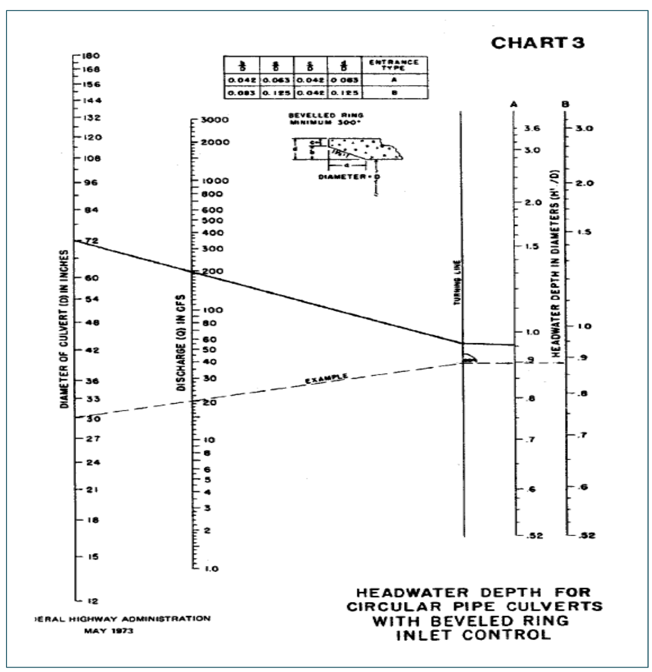
Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	*	X
Tailwater Elevation		X

*Barrel slope affects inlet control performance to a small degree, but may be neglected.

Computing Inlet Control Headwater

- For inlet control, capacity depends primarily on the geometry of the culvert entrance.
- Extensive laboratory tests by the National Bureau of Standards, the Bureau of Public Roads, and other entities resulted in a series of equations that describe the inlet control headwater under various conditions.
- These equations form the basis of the FHWA inlet control nomographs shown in the "Hydraulic Design of Highway Culverts" publication [FHWA, 1985].

Example of FHWA Culvert Charts

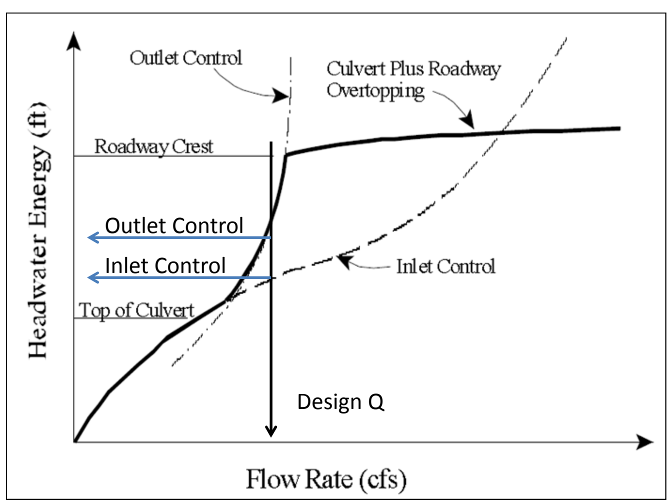


Example Culvert Inlets and Outlet

43

Optimizing Inlets and Outlets

- When inlet and outlet control energies equal, that combination is the most efficient.
- Investment in inlet/outlet works that does not “control” is a waste of money.



44

What is Grade Control?

- Prevention of Lowering of Channel elevation
  - Water Surface
  - Energy Grade
  - Bed Slope
- Limits
  - Valley Slope – Maximum
  - Cost / Space - Minimum

45

Small Drop/Grade Control Structure

46

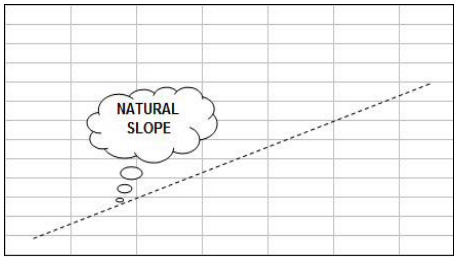
Types of Grade Control

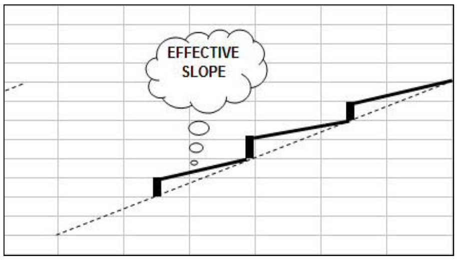
- Bed Control Structure
  - Provides a hard point to resist erosion
  - Reduction in bed slope reduces bed scour
  - May not have large upstream impact
- Hydraulic Control / Backwater Structure
  - Provides reduction in energy slope
  - Reduction in energy gradient – reduces velocity - reduces bed scour
  - Has impact upstream due to backwater

Why Consider Bed Stabilization / Grade Control?

- Stream Incising / General Lowering
- Migrating Headcut / Knickpoint
- Infrastructure at Risk
- Slope changes (natural and human causes)
- Slope Re-adjustment back to stable slope

Slope/Effective Slope





49

Headcut / Knickpoint

USDA-ARS-NSL

50

Streambed Stability Problem

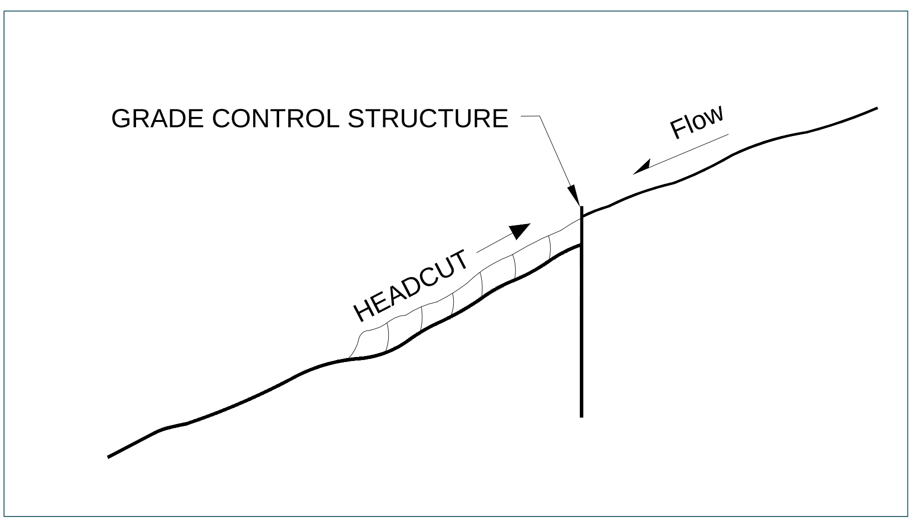
Pittman Wash,

Las Vegas

Even concrete channels can be undermined

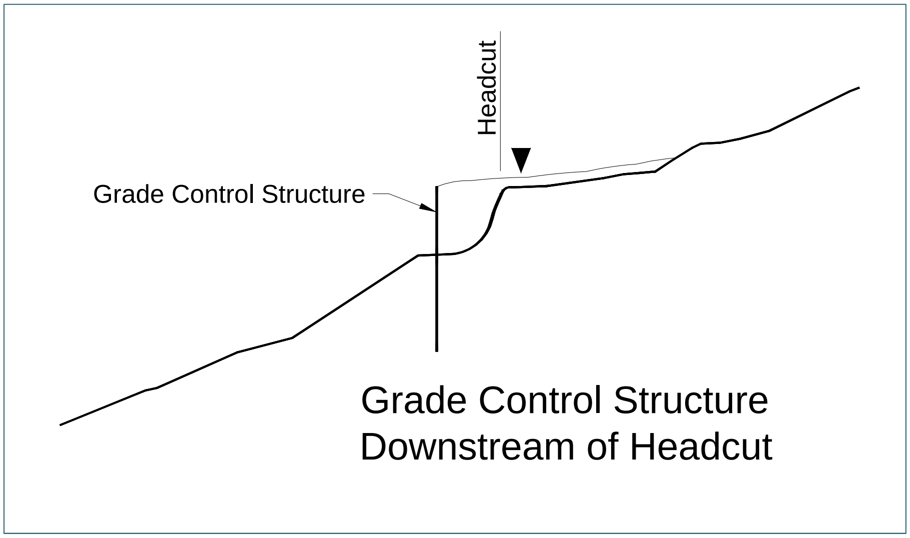
51

Bed/Grade Control Structure



52

Hydraulic Control Structure



53

Design Requirements for Grade Control

- Height of Drop / Change in WSE
- Drop Spacing – usually placed at riffle location if in a meandering stream
- Flow Depths
- Scour Depths – maximum is at the downstream end
- Evaluate Stability of structure
  - Sliding
  - Overturning
  - Uplift

54

Spacing of Drop/Grade Structures

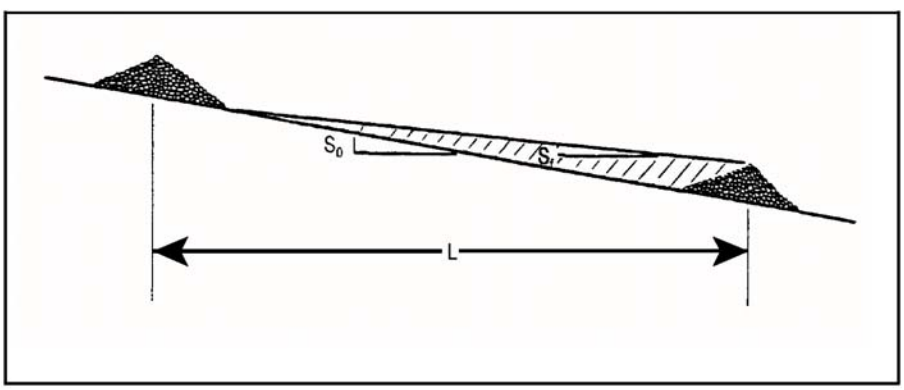
- $H = (S_o - S_f)\ L$
  - o S_o = Existing Slope
  - o S_f = Final (Desired/Stable) Slope
  - o L = Horizontal distance of reach
  - o H = Total vertical drop in bed elevation

- N = H/h
  - o h = Vertical drop at each structure
  - o N = Total number of structures

- Spacing of structures = L/N

55

Spacing Of Structures



56

Example 5 Problem

- Project length, L = 1,000 feet
- Equilibrium slope, S_o, = 0.01
- Existing slope, S_f, = 0.03 (too steep)
- Maximum drop for each structure, h = 3 feet

H = Total vertical drop = $(S_o - S_f)$ L = (0.03 – 0.01) x 1000 = 20 feet

N = Total number of structures = H/h = 20/3 = say 7

Spacing of structures = L/N = 1,000/7 = 143 feet

57

Grade Control Structures

- Drop Structure Types / Materials
  - Concrete
  - Sheetpile
  - Rock
  - Gabions
  - Soil Cement
  - Logs / Etc
  - Combinations

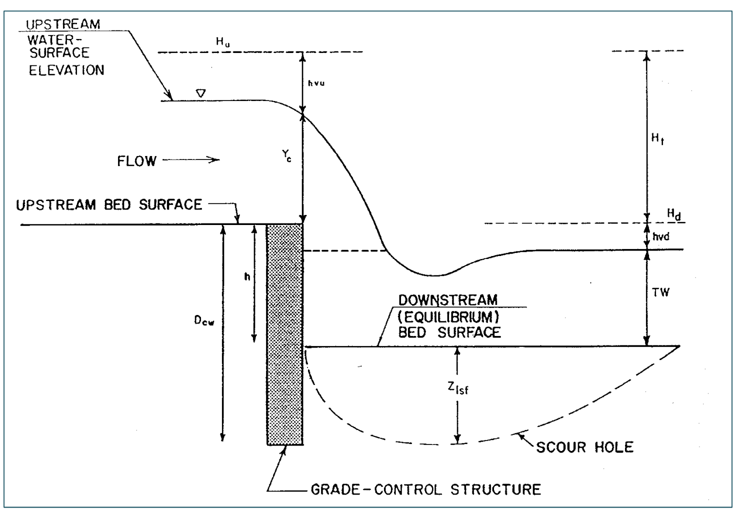
58

Structures with Preformed Scour Holes

- Scour holes will occur at any drop- man-made or natural.
- Structure must have sufficient launching rock.
  - o Prevent vertical scour immediately below weir
  - o Pre-formed scour hole with concrete, riprap and other non-erodible material is needed
  - o Serve as energy dissipaters for plunging flow
  - o Sizing must be based on experience or model studies

59

Drop Structure – Vertical Face



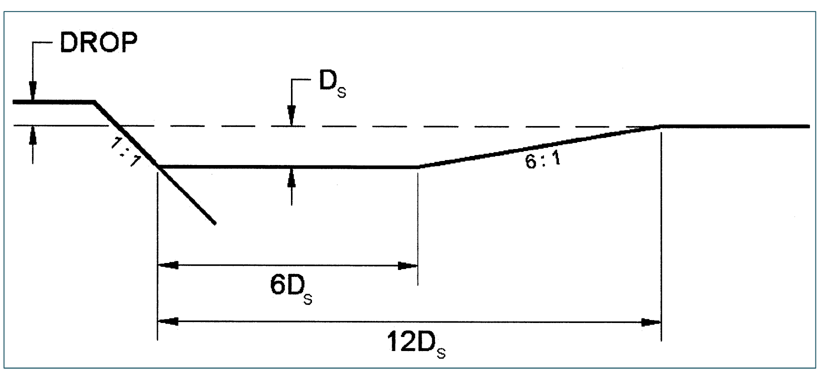
Depth of Scour Below a Free Overfall

60

Concrete Drop

61

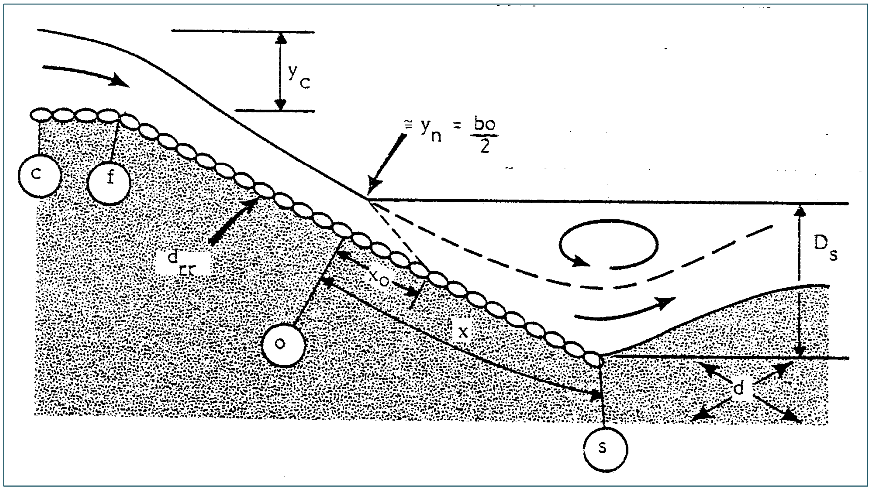
Grade Control w/1:1 Face Slope



Sketch of Scour Hole Downstream of Drop

62

Drop Structure w/4:1 Sloping Sill



Flow and Scour Pattern at a Sloping Sill

Drop Structure

Baffle Shoot Drop

65

Gabion Drop Structures

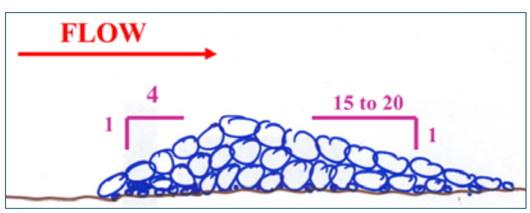
66

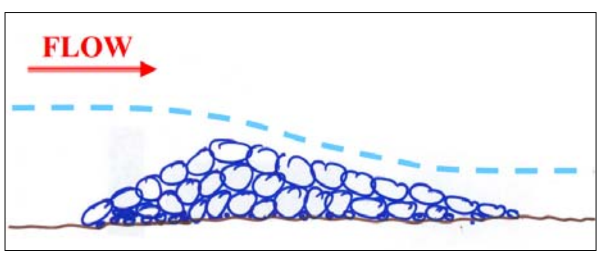
Other Types of Control Structures: for Low Drops

- **Rock**
  - Newberry Rock Riffles
  - Rock Vortex Weirs
  - Rock Cross Vanes
  - Step Pools
  - Rock Chutes
  - Etc.

67

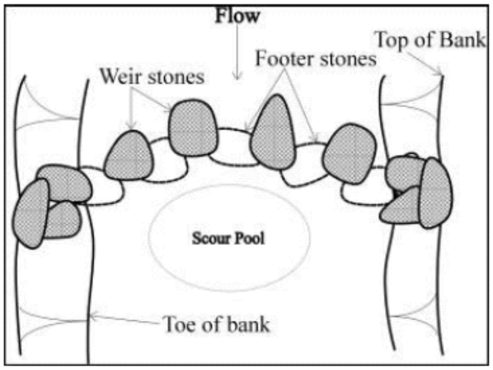
Newberry Rock Riffle



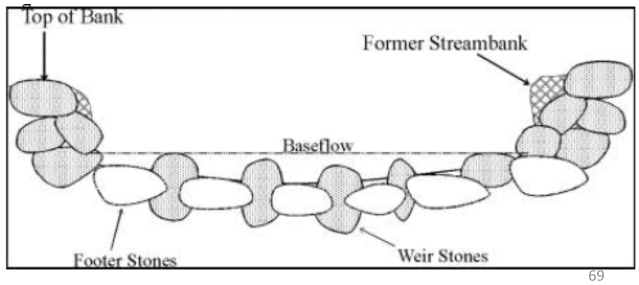


Largest stones are placed at crest and on downstream face, upstream face is in compression due to water flow.

68



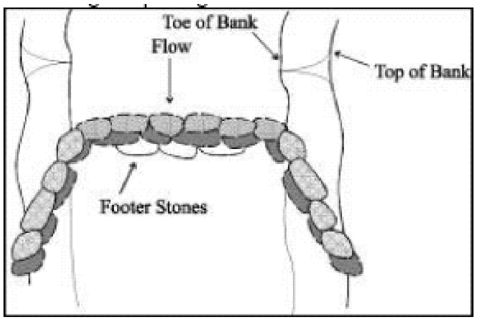
Rock Vortex Weirs



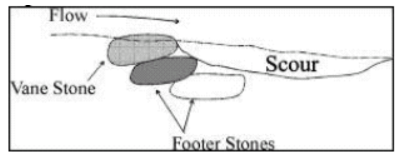
69

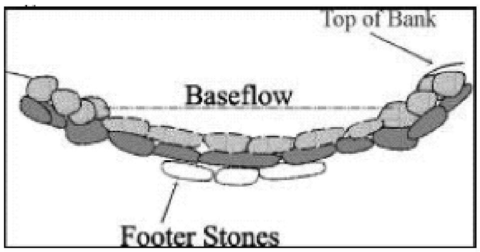
Rock Vortex Weir

70



Rock Cross Vanes





71

Rock Cross Vanes

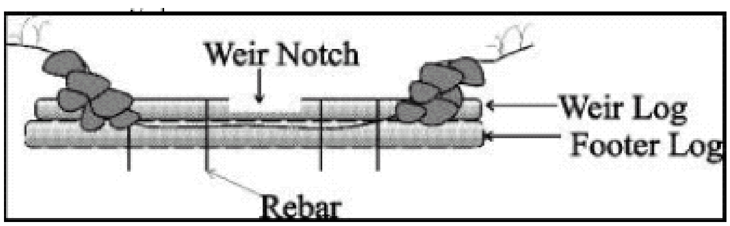
72

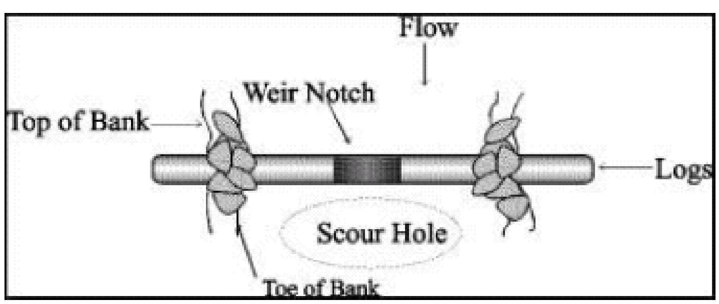
Additional Drop Structure Types “Environmentally Friendly”

- Log
  - Log Drops
  - V-Log Drops
- Use in Small Streams

73

Log Drop



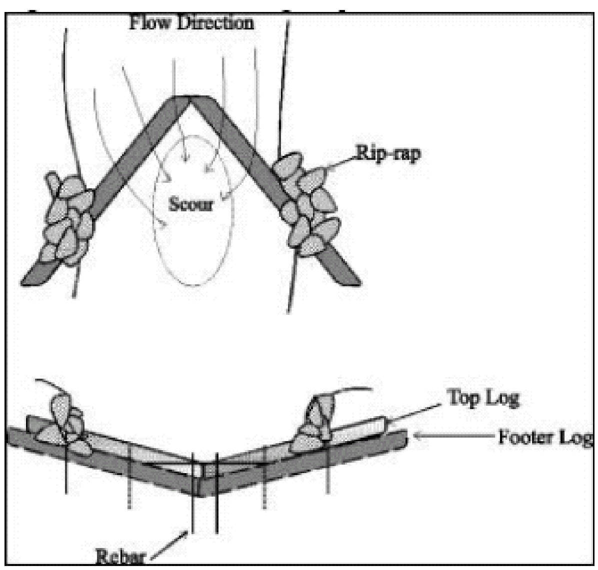


74

Log Drop

75

V-Log Drop



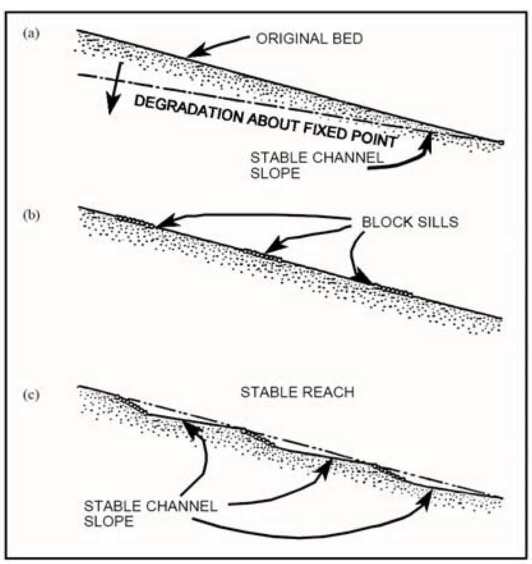
76

Simple Bed Controls

- Rock Sills – dumping of rock, concrete rubble, other non erodible material across channel
- Forms a hard point to resist erosive forces
- Can be placed on top of stream-bed or can be placed in a trench
- Sufficient volume is needed to counter general as well as local scour.

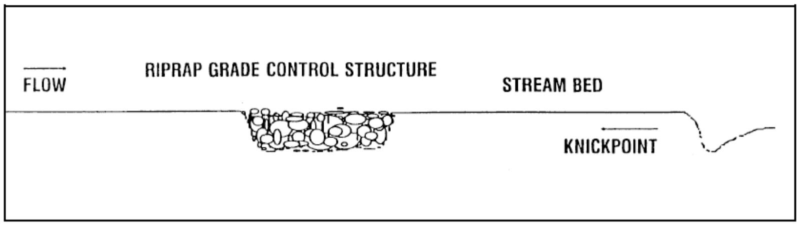
77

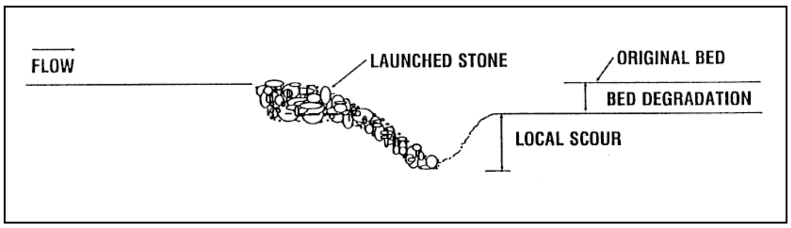
Simple Bed Controls – Rock Sills



78

Construction of Bed Sills





79

Questions?

80