

Sediment and Erosion Design Guide

SSCAFCA
AREA

Rio Grande

LOWL

EAST



Baranca
Arroyo

550

528



MEI

Bohannon  **Huston**

SANDIA MOUNTAINS

MANZANITA MOUNTAINS

Local Scour

Section 3.5

Dai Thomas, P.E.

Objectives

Local Scour

- Pier Scour
- Scour at grade control structures
- Revetments, Spurs and Abutments
- Culverts

Local Scour

Scour occurs where the flow is accelerated due to obstructions in the flow and involves the removal of bed and bank material

It occurs around:

Piers

Abutments

Spurs

Embankments

Downstream of grade control structures

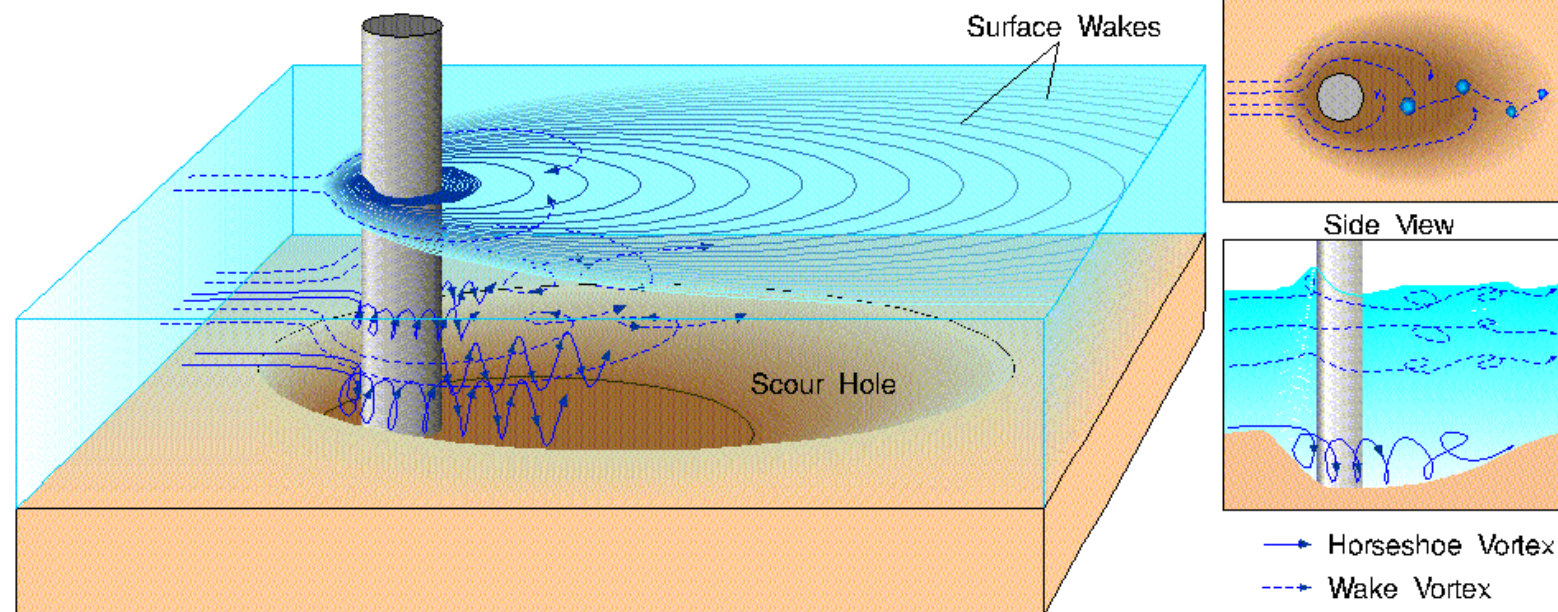
Local Scour

Principal erosion mechanism is the creation of vortices by the obstruction and the result and acceleration of flow

**Scour is cyclic – it scours on the rising limb
– it refills on the receding limb**

Pier Scour at Bridge Crossings

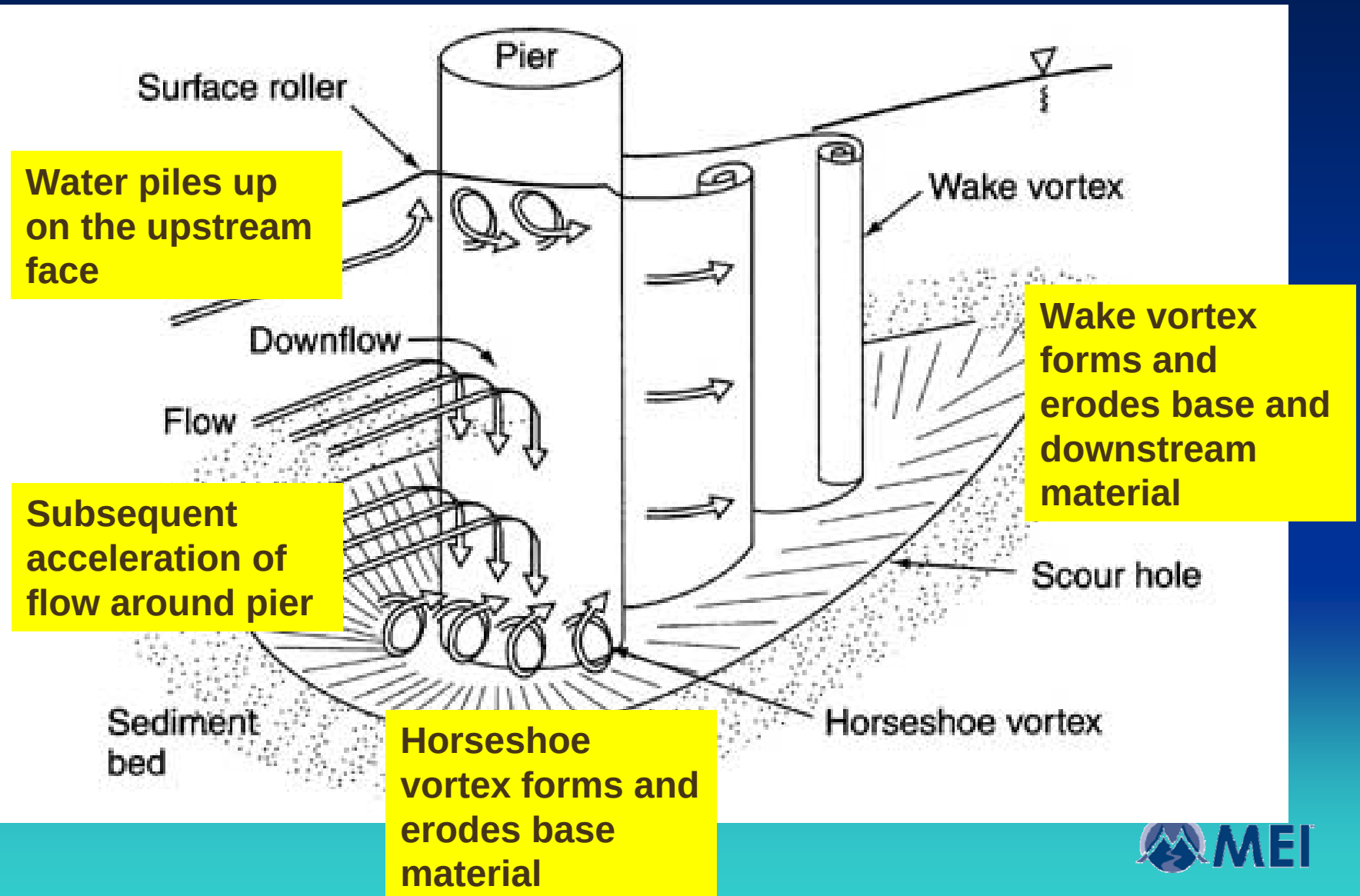
Horseshoe and Wake Vortices around a Cylindrical Element



Example of Pier Scour



Pier Scour at Bridge Crossings



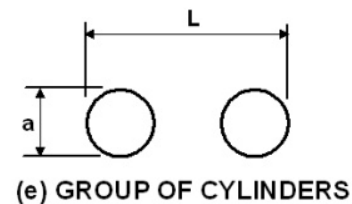
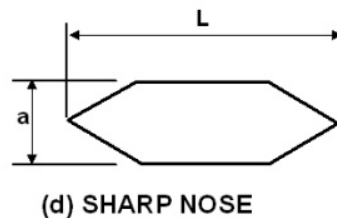
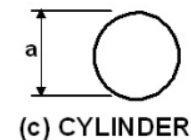
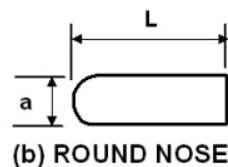
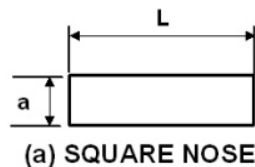
Factors affecting Pier Scour

1. Pier Width – greater pier width creates greater scour depth
2. Pier Length – no appreciable effect when the pier is aligned with the flow
 - **Has significant effect when skewed to flow**
3. Flow depth
4. Approach velocity
5. Angle of attack

Factors affecting Pier Scour

6. Shape of pier nose – more streamlined pier creates smaller vortex weir and less scour.

Square nose has - 20% greater scour than sharp-nosed pier
- 10% greater scour than round-nosed pier



Factors affecting Pier Scour

- 7. Debris – can increase the width of piers
 - can cause flow to plunge
 - increase local and contraction scour

Debris around piers



FHWA

Debris around piers



Louisiana (FHWA)

Factors affecting Pier Scour

- 7. Debris – can increase the width of piers
 - can cause flow to plunge
 - increase local and contraction scour

Can be taken into account in scour equation by increasing pier width

Factors affecting Pier Scour

8. Bed-material characteristics (size, gradation, cohesion)

- Sand sized material has no effect on local scour depth
- Larger-material will affect the maximum scour depth and influence the time it takes to attain it (**correction in manual**)
- Silts and Clays (have some cohesion) will scour as much as sand, but does influence the time it takes to attain maximum scour

Time to reach maximum scour depths

Sand-bed – hours (or single flood event)

Cohesive materials – days/months/years (many floods)

Factors affecting Pier Scour

9. Bed configuration (bedforms, i.e. ripples, dunes, plane-bed)

Affects:

- Magnitude of local scour
- Flow velocity
- Sediment transport

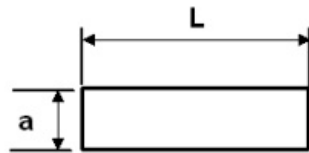
Computing Pier Scour

FWHA recommend the CSU Equation (Richardson & Davis, 2001)

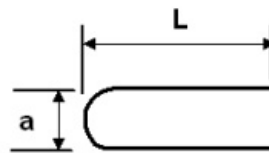
$$\frac{y_s}{y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{a}{y_1} \right)^{0.65} F_{r1}^{0.43} \quad (3.51)$$

where y_s = equilibrium scour depth, ft
 y_1 = flow depth just upstream of the pier, ft
 K_1 = correction for pier nose shape
 K_2 = correction for angle of attack of flow
 K_3 = correction for bed condition (i.e., bedform)
 K_4 = correction for armoring by bed-material size
 a = pier width, ft
 L = length of pier, ft
 F_{r1} = Froude Number = $V_1/\sqrt{gy_1}$ exponent based on conditions just upstream of the pier
 g = acceleration of gravity (32.2 ft/s²)

Common Pier Shapes



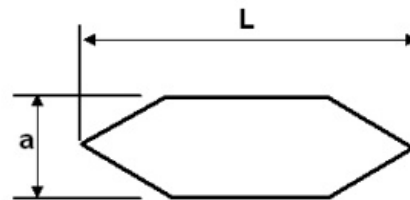
(a) SQUARE NOSE



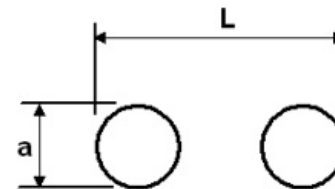
(b) ROUND NOSE



(c) CYLINDER



(d) SHARP NOSE



(e) GROUP OF CYLINDERS

Correction Factor K_1 for Pier Nose Shape

	Shape of Pier Nose	K_1
a.	Square nose	1.1
b.	Round nose	1.0
c.	Circular cylinder	1.0
d.	Sharp nose	0.9
e.	Group of cylinders	1.0

Correction Factor K_2 for Angle of Attack of the Flow

$$K_2 = (\cos \theta + L / a * \sin \theta)^{0.65}$$

Angle	L/a=4	L/a=8	L/a=12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

(3.52)

NB maximum L/a=12

Correction Factor K_3 for Bed Condition

Bed condition	Dune Height, (ft)	K_3
Clear-water scour	N/A	1.1
Plane bed and antidune flow	N/A	1.1
Small dunes	$9.8 > H \geq 1.97$	1.1
Medium dunes	$29.5 > H \geq 9.8$	1.2 to 1.1
Large dunes	$H \geq 29.5$	1.3

Correction Factor K_4 for Armoring

If $D_{50} < 2\text{mm}$ or $D_{95} < 20\text{mm}$, $K_4 = 1$

Else: $K_4 = 0.4(V_R)^{0.15}$ where: $V_R = \frac{V_1 - V_{icD_{50}}}{V_{cD_{50}} - V_{icD_{95}}} > 0$ (3.53)

(3.54)

V_{icD_x} = approach velocity (ft/s) required to initiate scour at the pier for the grain size D_x (ft)

$$V_{icD_x} = 0.645 \left(\frac{D_x}{a} \right)^{0.053} V_{cD_x} \quad (3.55)$$

$$V_{cD_x} = K_u y_1^{1/6} D_x^{1/3}$$

where y_1 = flow depth just upstream of the pier, excluding local scour, ft

V_1 = approach velocity just upstream of the pier, ft/s

D_x = grain size for which x percent of the bed material is finer, ft

$K_u = 11.17$ (English units)

Minimum value of $K_4 = 0.4$

Additional method of estimating scour for various complex bridge crossing configurations are in

FHWA Hydraulic Engineering Circular No.18

Address:

- **Pier scour correction for very wide piers**
- **Scour for complex pier foundations**
- **Multiple Columns skewed to flow**
- **Pressure Flow Scour**
- **Scour from debris on piers**
- **Top width of scour holes**



U.S. Department
of Transportation
**Federal Highway
Administration**

Publication No. FHWA NHI 01-001
May 2001

Hydraulic Engineering Circular No. 18

Evaluating Scour At Bridges

Fourth Edition



NATIONAL HIGHWAY INSTITUTE

Training Solutions for Transportation Excellence



Scour at Grade Control Structures



Stepped soil-cement erosion control structure on La Barranca Arroyo at Rio Rancho, New Mexico (Portland Cement Assoc.)

Accelerating flow over crest induces local scour immediately downstream, and resulting turbulence causes development of scour hole

Predicting Depth of Scour

Veronese Equation

$$d_s = K H_t^{0.225} q^{0.54} - d_m \quad (3.57)$$

d_s = local scour depth for a free overfall, measured from the streambed downstream of the drop, ft

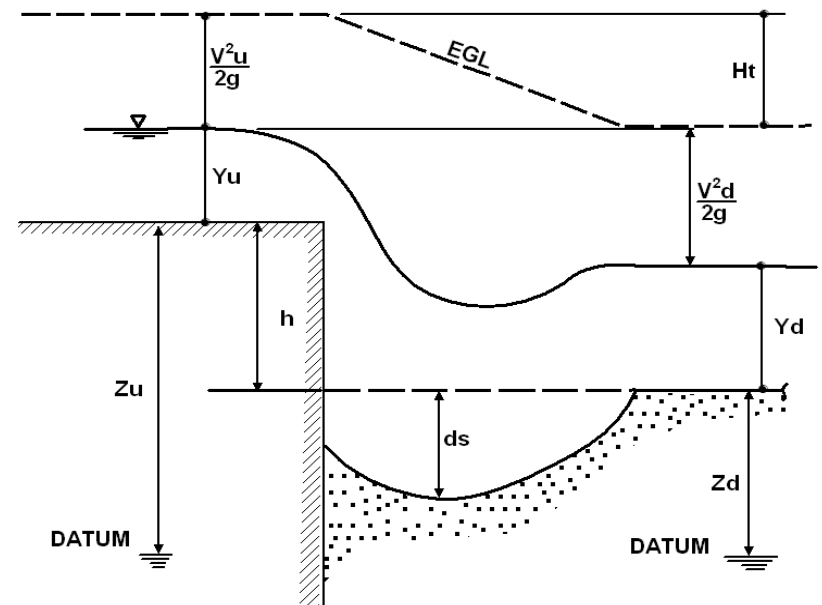
q = discharge per unit width, cfs per foot of width

H_t = total drop in head, measured from the upstream to the downstream energy grade line, ft

d_m = tailwater depth, ft

K = 1.32 (English Customary units)

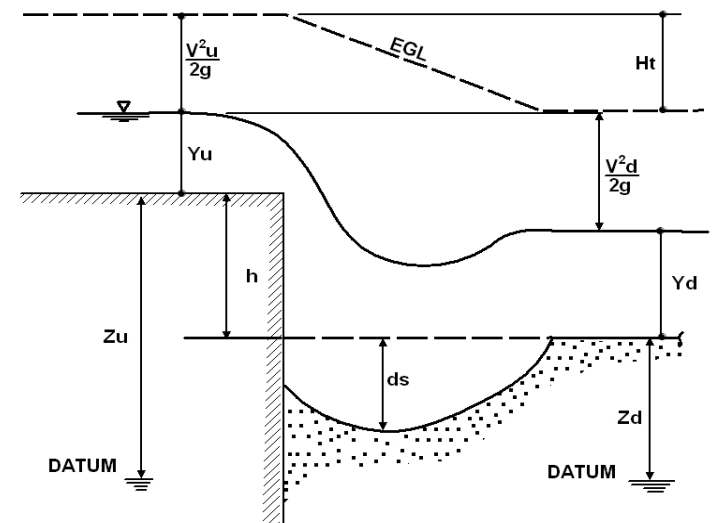
$$H_t = \left\{ Y_u + \frac{V_u^2}{2g} + Z_u \right\} - \left\{ Y_d + \frac{V_d^2}{2g} + Z_d \right\}$$



Predicting Depth of Scour

$$d_s = K H_t^{0.225} q^{0.54} - d_m \quad (3.57)$$

- Veronese Equation Typically provides very conservative results
- It only accounts for unit discharge and difference in hydraulic head across the dam
- Crest is vertical



Predicting Depth of Scour

Other Factors that affect the magnitude of scour:

- **Dissipation of hydraulic energy as flow plunges down a sloping face**
- **Dissipation of jet as it passes relatively deep tailwater flow on the downstream side**
- **Sediment Characteristics in the scour hole**

Predicting Depth of Scour

Bormann & Julien developed a more complex equation to account for these

Equation developed based on:

- **Hydraulic theory**
- **Laboratory data**
- **Field data**

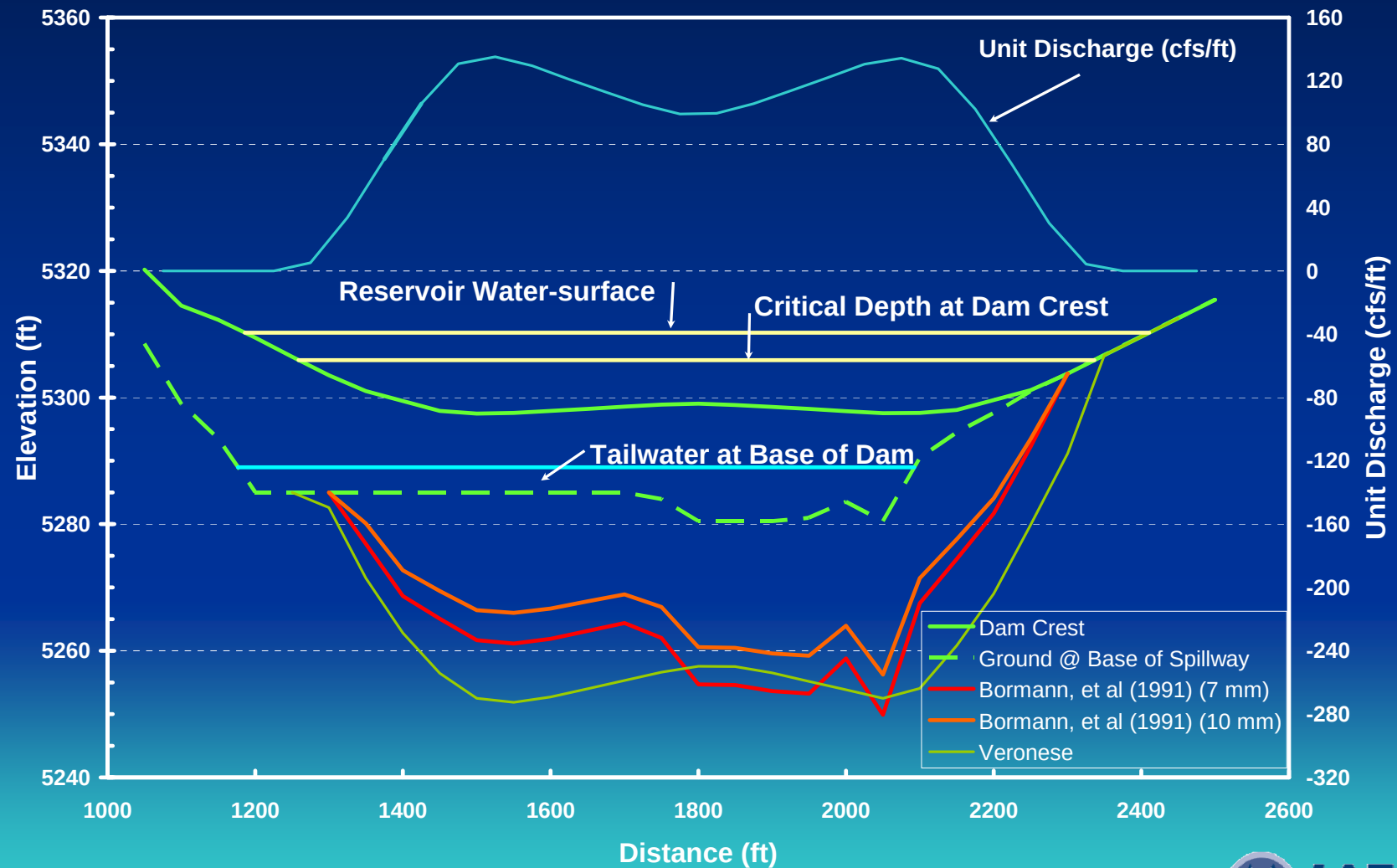
Predicting Depth of Scour

$$D_s = \left\{ \left[\frac{\gamma_s \sin \phi}{2(\gamma_s - \gamma)g \sin(\phi + \beta')} \right]^{0.8} \frac{3.24 Y_0^{0.6} U_0^{1.6}}{D_s^{0.4}} \sin \beta' \right\} - d_p \quad (3.59)$$

$$\beta' = 0.316 \sin \lambda + 0.15 \ln \left(\frac{D_p + Y_0}{Y_0} \right) + 0.13 \ln \left(\frac{Y_t}{Y_0} \right) - 0.05 \ln \left(\frac{U_0}{\sqrt{g Y_0}} \right) \quad (3.60)$$

where γ_s = unbulked unit weight of the sediment,
 γ = unit weight of water,
 ϕ = submerged angle of repose of the sediment (assumed to 25.5°),
 Y_0 = thickness of the jet as it impinges into the downstream tailwater,
 U_0 = velocity of the jet,
 Y_t = tailwater depth with respect to the original bed elevation,
 d_p = height of the embankment crest above the original bed,
 D_s = characteristic sediment size, and
 λ = angle of the emergency spillway with respect to horizontal.

Scour analysis at Sportsplex Dam



Scour at Grande Control Structures

Important to note:

Drop structure must be designed from a geotechnical and structural perspective to withstand the forces of water and soil assuming the full depth potential scour hole.

In some cases a series of drops may be used to minimize the drop height (and construction costs)

Riprap or energy dissipation could be used to limit the depth of scour.

Scour at Revetments, Spurs and Abutments

Local scour must be considered at obstructions such as:

Revetments

Base and end of revetments

Bridge abutments

FHWA Hydraulic Engineering Circular No.18 provides guidance for estimating local scour at these structures

Scour at Revetments, Spurs and Abutments

Equilibrium Scour Equation (for large a/Y_1).
Based on field measurements at rock dikes on the
Mississippi River

$$\frac{Y_s}{Y_1} = 4 F_{r1}^{0.33} \quad (3.61)$$

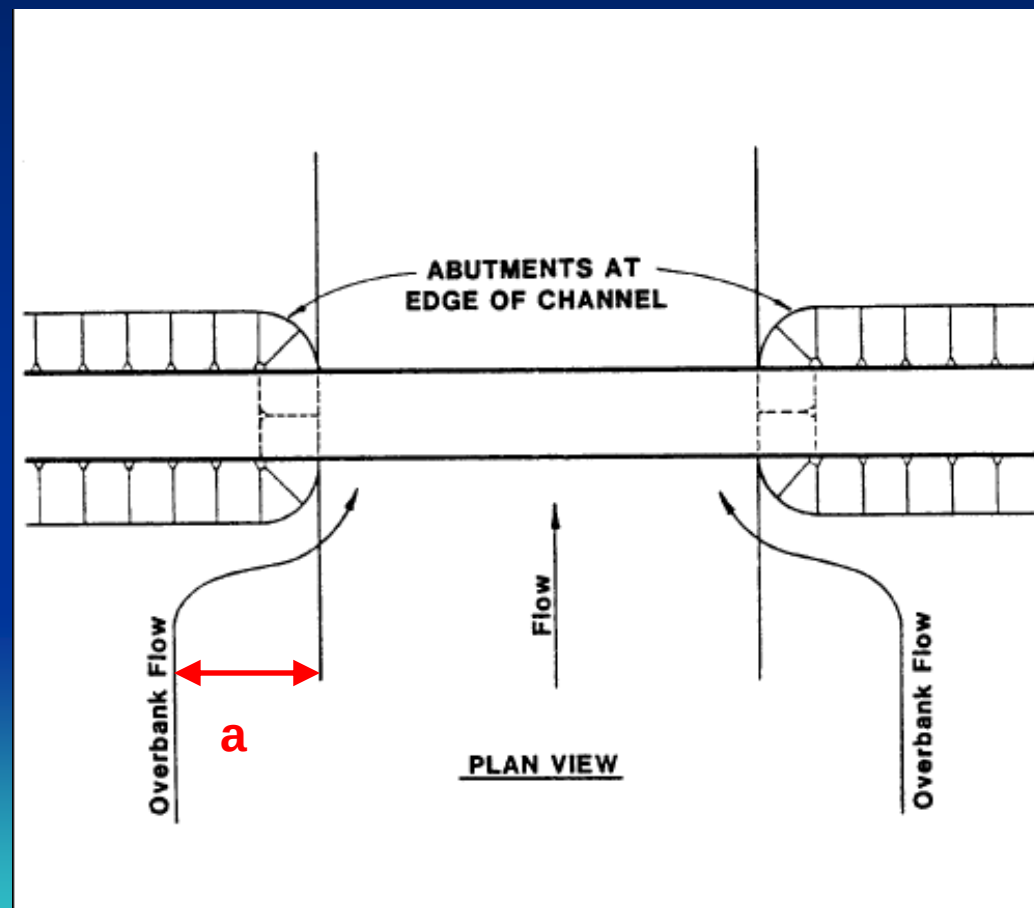
where Y_s = equilibrium depth of scour (measured from the mean bed level to the bottom of the scour hole),

Y_1 = average upstream flow depth in the main channel,

a = abutment and embankment or wall length projecting into main channel, and

F_{r1} = upstream Froude Number

a/Y_1 value



Scour along a floodwall

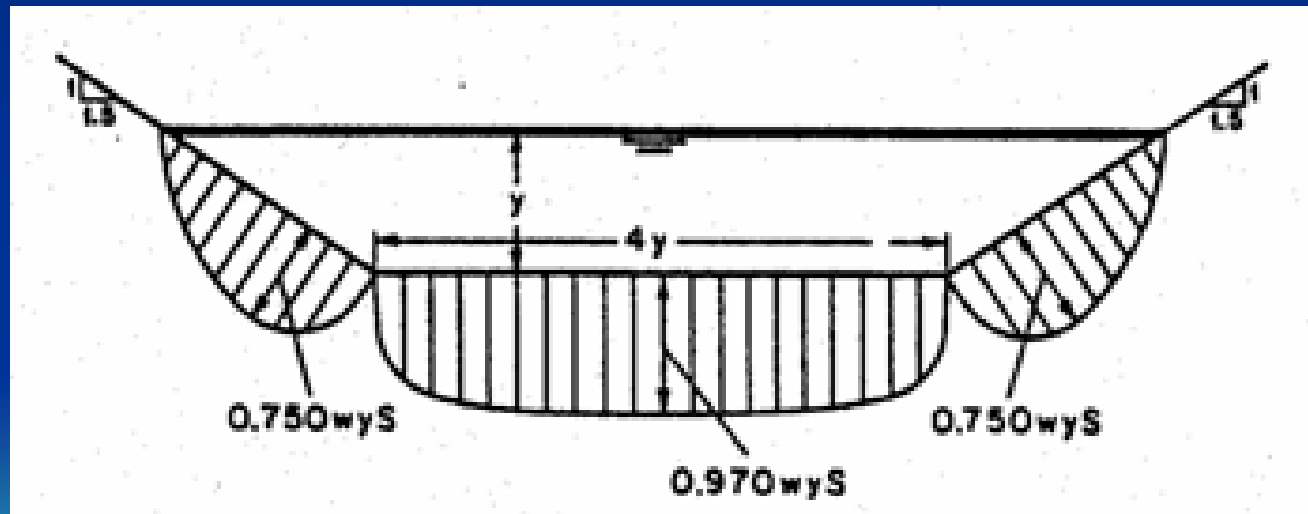
Scour along floodwall due to:

- **increased shear stress caused by locally high velocities along the smooth face of the wall**
- **Flow impinging directly into the wall**



Scour along a floodwall

- Shear stress along a trapezoid channel is not uniform
- Peak occurs at centre of channel
- Secondary peak $\sim 1/3$ of the distance up the side slope



Scour along a floodwall

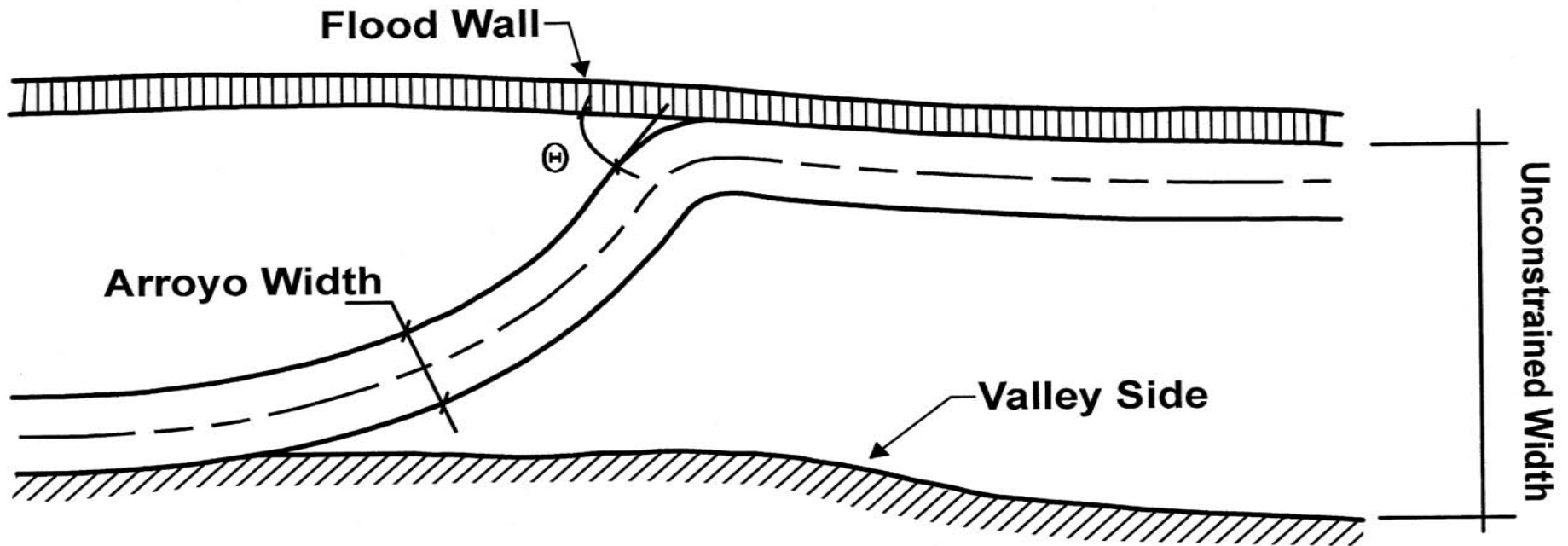
First Approximation for scour along a smooth floodwall can be made from (Mussetter et al. 1994):

$$\frac{Y_s}{Y_1} = 0.73 + 0.14\pi F_r^2 \quad (3.62)$$

1st term - Based on observation that the smooth floodwall will increase the conveyance in the vicinity of the wall, which will cause the channel bed to scour so that the local shear stress will be in balance with the rougher supply areas immediately upstream

2nd term – accounts for effect of antidune scour in vicinity of wall

Flow Impinging Wall at an Angle



Flow Impinging Wall at an Angle

Flow impinges at $\sim 90^\circ$ Angle

$$\frac{Y_s}{Y_1} = 4 F_{r_1}^{0.33} \quad (3.61)$$

Flow parallel to wall

$$\frac{Y_s}{Y_1} = 0.73 + 0.14\pi F_r^2 \quad (3.62)$$

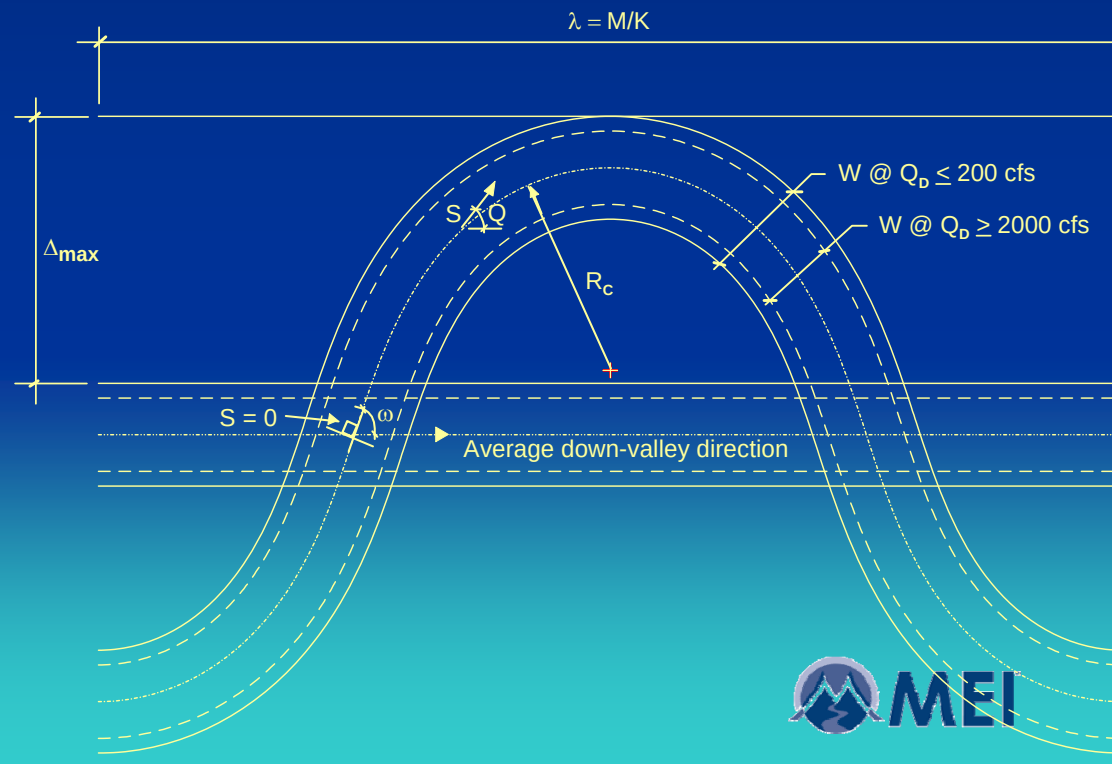
$$\frac{Y_s}{Y_1} = (0.73 + 0.14\pi F_r^2) \cos \theta + 4 F_r^{0.33} \sin \theta \quad (3.63)$$

where θ = angle between the flow direction and the floodwall



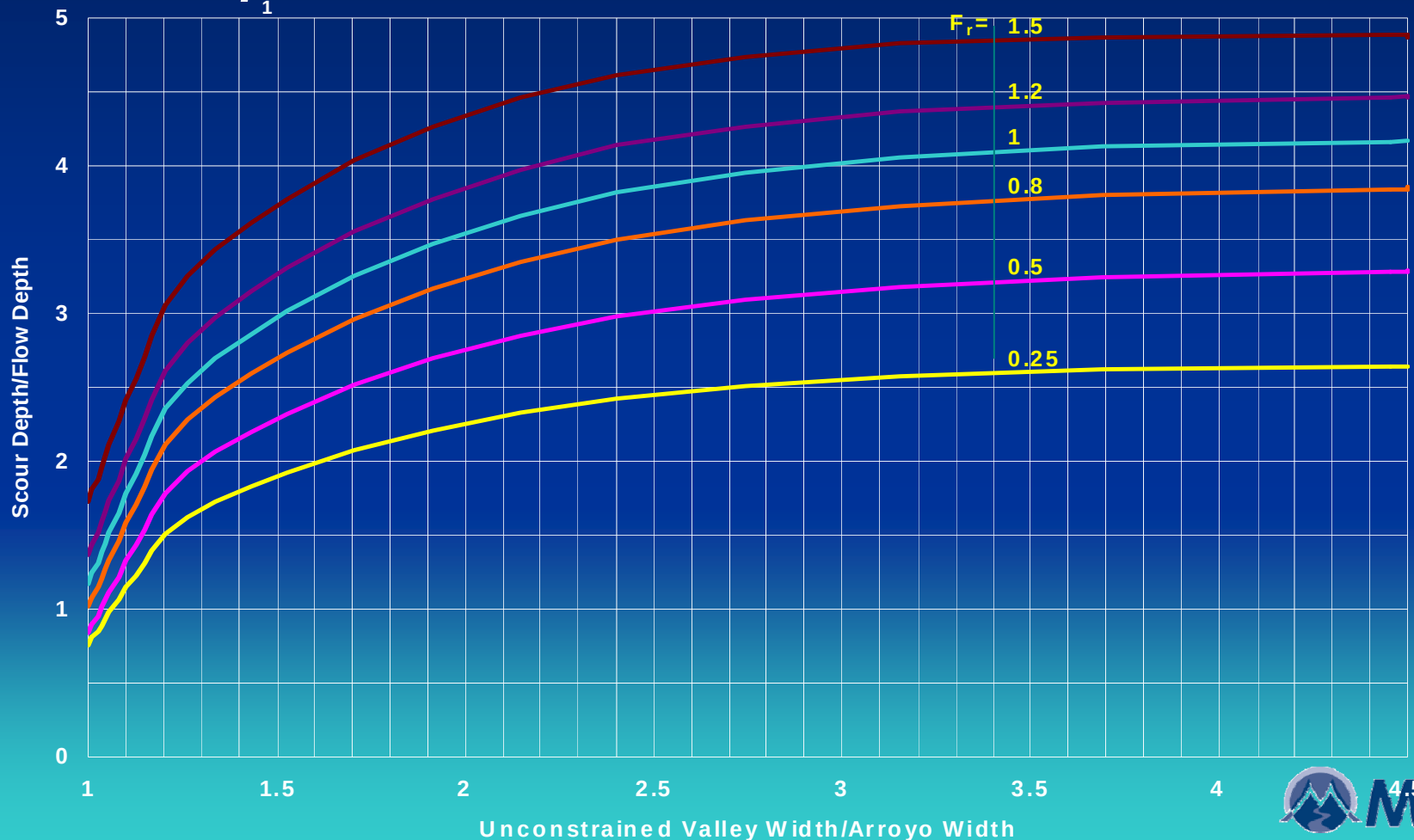
Scour along floodway in Relation to Unconstrained Valley Width

In a ideal meander geometry:
minimum impingement angle = 0° (parallel)
maximum impingement angle $\sim 71^\circ$
(assuming unconstrained valley width 3.5 time arroyo width
and meander wave length 14 times channel width)



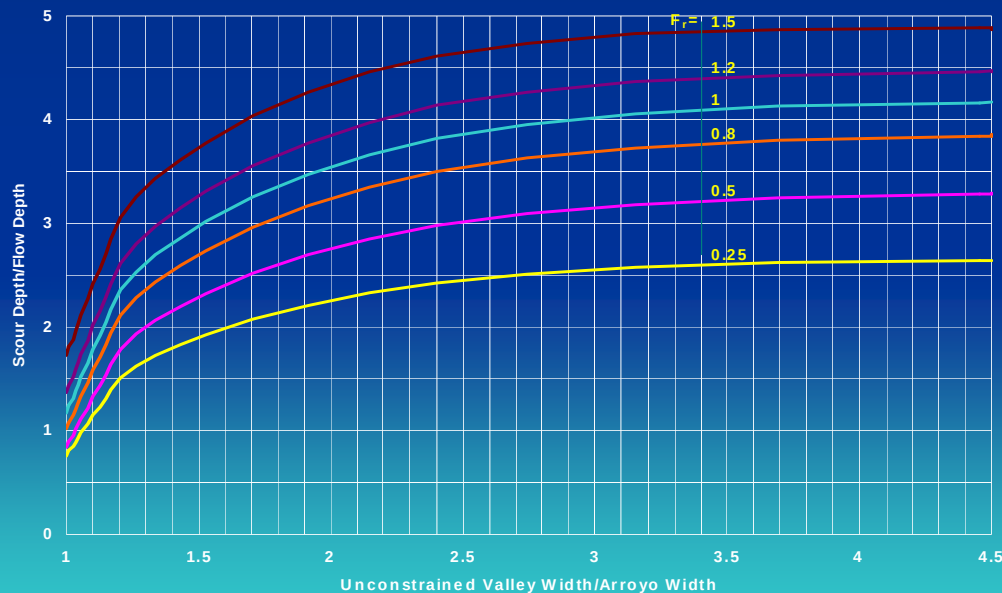
Scour along floodway in Relation to Unconstrained Valley Width

$$\frac{Y_s}{Y_1} = (0.73 + 0.14\pi F_r^2) \cos \theta + 4F_r^{0.33} \sin \theta$$



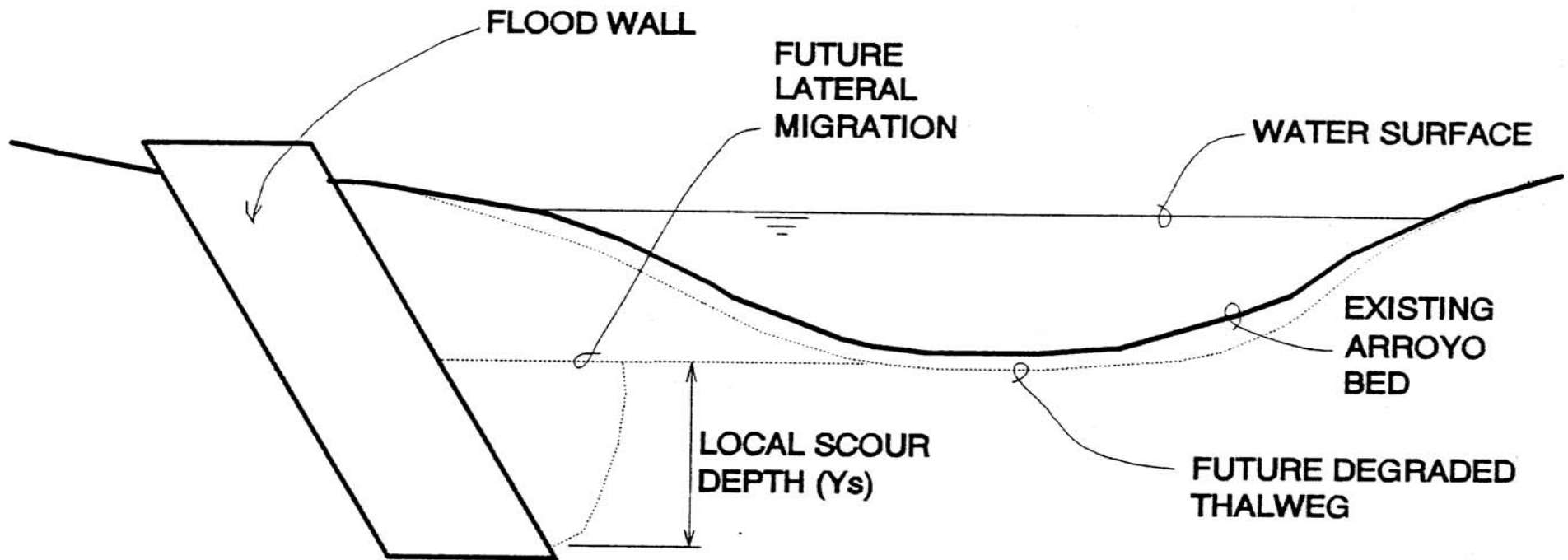
Scour along floodway in Relation to Unconstrained Valley Width

- Based on assumed ideal meander geometry and scour relationships
- Very approximate
- Use engineering judgment due local variability



Scour along a floodwall

Scour depth should be measured from channel Thalweg and accounting for potential effects of future degradation



Local Scour at Culverts

Scour hole geometry given by:

$$A^* = \alpha \left(\frac{Q}{\sqrt{gD^{5/2}}} \right)^\beta \left(\frac{t}{t_o} \right)^\theta \quad (3.64)$$

where A^* = the dimensionless scour geometry, (h_s/D , W_s/D , L_s/D , or V_s/D^3) and (h_s/y_e , W_s/y_e , L_s/y_e , or V_s/y_e^3),

Q = discharge,

g = acceleration of gravity,

D = culvert diameter,

t = duration of the flow, and

t_o = 316 minutes (the base time used in the experiments upon which the relations are based).

Check Dams (Drops)

A. Check dams are used to mitigate vertical instability problems.

- **Used to maintain a stable bed elevation**
- **Arrest head cuts**

B. Design considerations.

- **Scour depth downstream of drop**
- **Number of drop structures**
- **Bank erosion**

Check Dams (Drops)

C. Design problem.

Given:

Design Discharge	Q	=1000 ft ³ /s
Channel Width	B	= 40 feet
Mean Water Depth*	d _m	= 2.7 feet
Unit Discharge	Q	= 25 ft ³ /s/ft
Mean Velocity*	V	= 9.26 ft/s
Total Drop Height	H	= 5 feet
Maximum Allowable Scour Depth	d _s	= 7 feet

*For this example, the depth and velocity is the same up- and downstream.

From Energy Equation: $Z_u - Z_d = H_T = \text{drop height}$
See Figure 3.22 for definition of variables.

Check Dams (Drops)

Example Problem #1

1. Determine the maximum scour depth (single check dam).

Use the Veronese Equation (Equation 3.57)

$$d_s = 1.32 H_t^{0.225} q^{0.54} - d_m$$

$$= 1.32 (5.0)^{0.225} (25)^{0.54} - 2.7$$

$$= 8.08 \text{ ft}$$

Design Discharge	Q	=1000 ft ³ /s
Channel Width	B	= 40 feet
Mean Water Depth*	d _m	= 2.7 feet
Unit Discharge	Q	= 25 ft ³ /s/ft
Mean Velocity*	V	= 9.26 ft/s
Total Drop Height	H	= 5 feet
Maximum Allowable Scour Depth	d _s	= 7 feet



Check Dams (Drops)

Example Problem #2

2. Use multiple drops if scour is too deep.

Decrease drop height and use more drops.

Estimate drop for scour depth of 7 feet:

$$7 = 1.32 H_{max}^{.225} (25)^{.54} - 2.7$$

$$H_{max} = 3.12 \text{ ft}$$

Re-compute scour depth.

Number of equally spaced drops required = 2

Drop height per drop = $5/2=2.50$ feet

$$d_s = (1.32) (2.5)^{.225} (25)^{.54} - 2.7 = 6.5 \text{ ft} < 7'$$

Scour depth per drop, $d_s = 6.5 \text{ feet} < 7' \text{ (given)}$

Check Dams (Drops)

Example Problem #3

3. Adequately protect banks downstream of check dam

- a. Riprap protection ~ 5 to 10 times d_s in downstream direction
- b. Other considerations - use equilibrium slope to determine spacing of drops and the total drop height

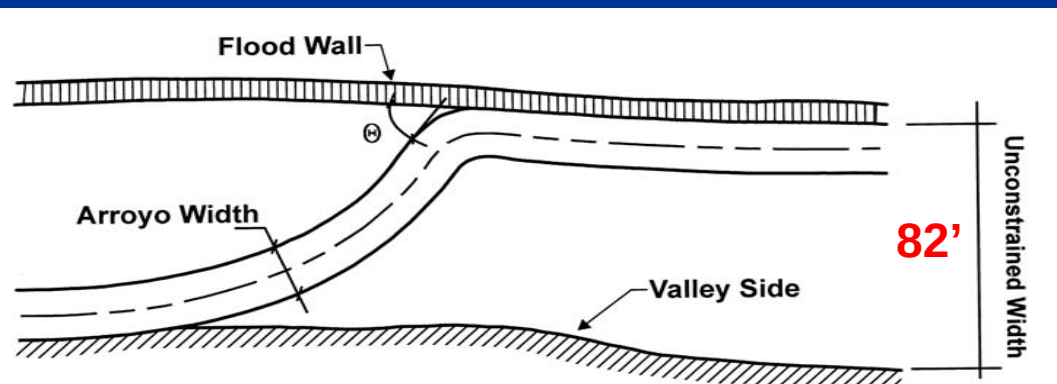
Local Scour at Floodwall

A flood wall will be constructed along one side of the given arroyo to limit the lateral erosion potential. The unconstrained valley width after construction of the wall will be 82 feet, $S_0=0.022$

Estimate the scour depth along the wall at the peak of the 100-year flood.

Estimate the dominant arroyo width (WD):

$$Q_D = 0.2 * Q_{100} = (0.2) (500) = 100 \text{ cfs}$$



Local Scour at Floodwall

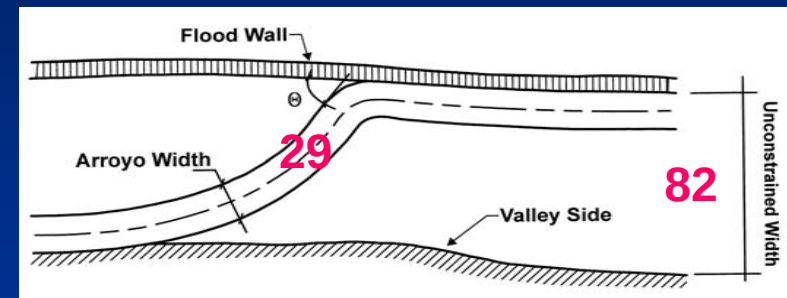
Calculate dominant width

$$W_D = (4.6)(100)^{0.4} = 29.0 \text{ feet} \quad (3.36)$$

Local Scour at Floodwall

Estimate the ratio of unconstrained valley width to channel width:

$$W_v / W_D = 82/29 = 2.83$$



Determine the Froude number for the 100-year flood peak:

Find the normal depth from Manning's equation:

$$y = \frac{\left(\frac{Q}{W}\right)n}{1.486\sqrt{S_0}}$$

$$y = [(500/29) * 0.035 / 1.486 / \sqrt{0.022}]^{3/5} = 1.83 \text{ feet}$$

Local Scour at Floodwall

$$V = \frac{Q}{W \cdot y}$$

$$V = \frac{500}{29 \cdot 1.83} = 9.42 \text{ fps}$$

$$F_r = (9.42) / \sqrt{(g)(1.83)} = 1.23$$

$$D_{sc} / y = 4.4$$

$$D_{sc} = (4.4)(1.83) = 8.0 \text{ feet}$$

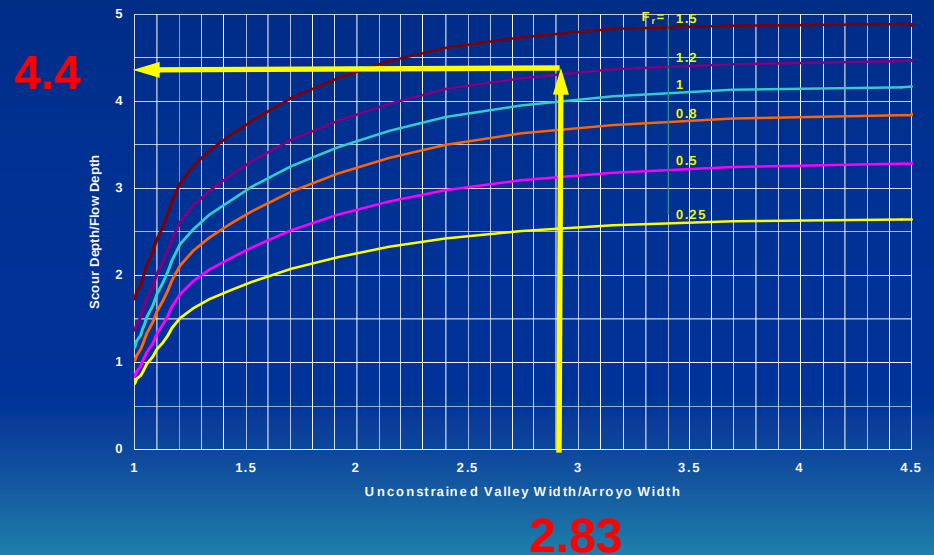


Figure 3.24

Thank you

