Sediment and Erosion Design Guide
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

- Scour Hole
- Surface Wakes
- Top View
- Side View
- Horseshoe Vortex
- Wake Vortex
Example of Pier Scour
Pier Scour at Bridge Crossings

Water piles up on the upstream face.

Subsequent acceleration of flow around pier forms a horseshoe vortex, which erodes the base material.

Wake vortex forms and erodes the base and downstream material.
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)

\[ \frac{y_s}{y_1} = 2.0 K_1 K_2 K_3 K_4 \left( \frac{a}{y_1} \right)^{0.65} F_{r_1}^{0.43} \]  

(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
- \( F_{r_1} \) = Froude Number = \( \frac{V_1}{\sqrt{gy_1}} \) 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

<table>
<thead>
<tr>
<th>Shape of Pier Nose</th>
<th>$K_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Square nose</td>
<td>1.1</td>
</tr>
<tr>
<td>b. Round nose</td>
<td>1.0</td>
</tr>
<tr>
<td>c. Circular cylinder</td>
<td>1.0</td>
</tr>
<tr>
<td>d. Sharp nose</td>
<td>0.9</td>
</tr>
<tr>
<td>e. Group of cylinders</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Correction Factor $K_2$ for Angle of Attack of the Flow

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

<table>
<thead>
<tr>
<th>Angle</th>
<th>L/a=4</th>
<th>L/a=8</th>
<th>L/a=12</th>
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<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>30</td>
<td>2.0</td>
<td>2.75</td>
<td>3.5</td>
</tr>
<tr>
<td>45</td>
<td>2.3</td>
<td>3.3</td>
<td>4.3</td>
</tr>
<tr>
<td>90</td>
<td>2.5</td>
<td>3.9</td>
<td>5.0</td>
</tr>
</tbody>
</table>

NB maximum L/a=12

Correction Factor $K_3$ for Bed Condition

<table>
<thead>
<tr>
<th>Bed condition</th>
<th>Dune Height, (ft)</th>
<th>$K_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear-water scour</td>
<td>N/A</td>
<td>1.1</td>
</tr>
<tr>
<td>Plane bed and antidune flow</td>
<td>N/A</td>
<td>1.1</td>
</tr>
<tr>
<td>Small dunes</td>
<td>$9.8 &gt; H &gt;= 1.97$</td>
<td>1.1</td>
</tr>
<tr>
<td>Medium dunes</td>
<td>$29.5 &gt; H &gt;= 9.8$</td>
<td>1.2 to 1.1</td>
</tr>
<tr>
<td>Large dunes</td>
<td>$H &gt;= 29.5$</td>
<td>1.3</td>
</tr>
</tbody>
</table>
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)

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

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

(3.55)

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

where $y_1 = \text{flow depth just upstream of the pier, excluding local scour, ft}$  

$V_1 = \text{approach velocity just upstream of the pier, ft/s}$  

$D_x = \text{grain size for which } x \text{ percent of the bed material is finer, ft}$  

$K_u = 11.17 \text{ (English units)}$

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
Evaluating Scour At Bridges
Fourth Edition
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

\[ d_s = K H_t^{0.225} q^{0.54} - d_m \]  \hspace{1cm} (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

\[ d_s = K H_t^{0.225} q^{0.54} - d_m \]  (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
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

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

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

where

- \( \gamma_s \) = unbulked unit weight of the sediment,
- \( \gamma \) = unit weight of water,
- \( \phi \) = submerged angle of repose of the sediment (assumed to 25.5\(^\circ\)),
- \( Y_0 \) = 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
- \( \lambda \) = angle of the emergency spillway with respect to horizontal.
Scour analysis at Sportsplex Dam

- Reservoir Water-surface
- Critical Depth at Dam Crest
- Tailwater at Base of Dam

Graph showing:
- Unit Discharge (cfs/ft)
- Elevation (ft)
- Distance (ft)

Lines representing:
- Dam Crest
- Ground @ Base of Spillway
- Bormann, et al (1991) (7 mm)
- Bormann, et al (1991) (10 mm)
- Veronese

Critical Depth at Dam Crest and Tailwater at Base of Dam are indicated on the graph.
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

\[
\frac{Y_s}{Y_1} = 4 \left( \frac{Fr_1}{Y_1} \right)^{0.33}
\]  (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
\(Fr_1\) = 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 ~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 (Mussettel et al. 1994):

\[ \frac{Y_s}{Y_1} = 0.73 + 0.14\pi F_r^2 \]  

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

- Flood Wall
- Arroyo Width
- Valley Side

Unconstrained Width
Flow Impinging Wall at an Angle

Flow impinges at ~90° Angle

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

Flow parallel to wall

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

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

where \( \theta \) = 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 = $0^\circ$ (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

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

- **Fr** = 0.25
- **Fr** = 0.5
- **Fr** = 0.8
- **Fr** = 1
- **Fr** = 1.2
- **Fr** = 1.5

Scour Depth/Flow Depth vs. Unconstrained Valley Width/Arroyo Width
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:

\[ A^* = \alpha \left( \frac{Q}{\sqrt{gD^{5/2}}} \right)^\beta \left( \frac{t}{t_0} \right)^\theta \]  

(3.64)

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

\( Q \) = discharge,

\( g \) = acceleration of gravity,

\( D \) = culvert diameter,

\( t \) = duration of the flow, and

\( t_0 \) = 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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Discharge</td>
<td>Q</td>
<td>1000 ft³/s</td>
</tr>
<tr>
<td>Channel Width</td>
<td>B</td>
<td>40 feet</td>
</tr>
<tr>
<td>Mean Water Depth*</td>
<td>dₘ</td>
<td>2.7 feet</td>
</tr>
<tr>
<td>Unit Discharge</td>
<td>Q</td>
<td>25 ft³/s/ft</td>
</tr>
<tr>
<td>Mean Velocity*</td>
<td>V</td>
<td>9.26 ft/s</td>
</tr>
<tr>
<td>Total Drop Height</td>
<td>H</td>
<td>5 feet</td>
</tr>
<tr>
<td>Maximum Allowable Scour Depth</td>
<td>dₛ</td>
<td>7 feet</td>
</tr>
</tbody>
</table>

*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
2. Use multiple drops if scour is too deep.

Decrease drop height and use more drops.

Estimate drop for scour depth of 7 feet:

\[ 7 = 1.32 \cdot H_{\text{max}}^{225} \cdot (25)^{.54} - 2.7 \]

\[ H_{\text{max}} = 3.12 \text{ ft} \]

Re-compute scour depth.

Number of equally spaced drops required = 2

Drop height per drop = \( \frac{5}{2} = 2.50 \text{ feet} \)

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

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

$$Q_D = 0.2 \times Q_{100} = (0.2) (500) = 100 \text{ cfs}$$
Local Scour at Floodwall

Calculate dominant width

\[ W_D = (4.6) (100)^{0.4} = 29.0 \text{ feet} \]  

(3.36)
Local Scour at Floodwall

Estimate the ratio of unconstrained valley width to channel width:

\[ \frac{W_v}{W_D} = \frac{82}{29} = 2.83 \]

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

Find the normal depth from Manning’s equation:

\[ y = \left( \frac{Q}{W} \right)^n \times \frac{1.486}{\sqrt{S_0}} \]

\[ y = \left[ \frac{(500/29) \times 0.035/1.486}{\sqrt{0.022}} \right]^{3/5} = 1.83 \text{ feet} \]
Local Scour at Floodwall

\[ V = \frac{Q}{W \cdot y} \]

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

\[ F_r = \frac{9.42}{\sqrt{g(1.83)}} = 1.23 \]

\[ D_{sc} / y = 4.4 \]

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

Figure 3.24
Thank you