CHAPTER 10

Estimating Scour at Bridges

The computation of scour at bridges within HEC-RAS is based upon the methods outlined in Hydraulic Engineering Circular No. 18 (HEC No. 18, FHWA, 1995). Before performing a scour analysis with the HEC-RAS software, the engineer should thoroughly review the procedures outlined in that report. This chapter presents the methods and equations for computing contraction scour and local scour at piers and abutments. Most of the material in this chapter was taken directly from the HEC No. 18 publication (FHWA, 1995).

For information on how to enter bridge scour data into HEC-RAS, to perform the bridge scour computations, and to view the bridge scour results, see Chapter 11 of the HEC-RAS user's manual.

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General Modeling Guidelines

In order to perform a bridge scour analysis, the user must first develop a hydraulic model of the river reach containing the bridge to be analyzed. This model should include several cross sections downstream from the bridge, such that any user defined downstream boundary condition does not affect the hydraulic results inside and just upstream of the bridge. The model should also include several cross sections upstream of the bridge, in order to evaluate the long-term effects of the bridge on the water surface profile upstream.

The hydraulic modeling of the bridge should be based on the procedures outlined in Chapter 5 of this manual. If observed data are available, the model should be calibrated to the fullest extent possible. Once the hydraulic model has been calibrated (if observed data are available), the modeler can enter the design events to be used for the scour analysis. In general, the design event for a scour analysis is usually the 100 year (1 percent chance) event. In addition to this event, it is recommended that a 500 year (0.2 percent chance) event also be used to evaluate the bridge foundation under a super-flood condition.

After performing the water surface profile calculations for the design events, the bridge scour can then be evaluated. The total scour at a highway crossing is comprised of three components: long-term aggradation or degradation; contraction scour; and local scour at piers and abutments. The scour computations in the HEC-RAS software allow the user to compute contraction scour and local scour at piers and abutments. The current version of the HEC-RAS software does not allow the user to evaluate long-term aggradation and degradation. Long term aggradation and degradation should be evaluated before performing the bridge scour analysis. Procedures for performing this type of analysis are outlined in the HEC No. 18 report, and are beyond the scope of this discussion. The remaining discussions in this chapter are limited to the computation of contraction scour and local pier and abutment scour.

Computing Contraction Scour

Contraction scour occurs when the flow area of a stream is reduced by a natural contraction or a bridge constricting the flow. At a bridge crossing, many factors can contribute to the occurrence of contraction scour. These factors may include: the main channel naturally contracts as it approaches the bridge opening; the road embankments at the approach to the bridge cause all or a portion of the overbank flow to be forced into the main channel; the bridge abutments are projecting into the main channel; the bridge piers are blocking a significant portion of the flow area; and a drop in the downstream tailwater which causes increased velocities inside the bridge. There are two forms of contraction scour that can occur depending on how much bed material is already being transported upstream of the bridge contraction reach.

The two types of contraction scour are called live-bed contraction scour and clear-water contraction scour. Live-bed contraction scour occurs when bed material is already being transported into the contracted bridge section from upstream of the approach section (before the contraction reach). Clear-water contraction scour occurs when the bed material sediment transport in the uncontracted approach section is negligible or less than the carrying capacity of the flow.

Contraction Scour Conditions

Four conditions (cases) of contraction scour are commonly encountered:

Case 1. Involves overbank flow on a floodplain being forced back to the main channel by the approaches to the bridge. Case 1 conditions include:

a. The river channel width becomes narrower either due to the bridge abutments projecting into the channel or the bridge being located at a narrowing reach of the river.

b. No contraction of the main channel, but the overbank flow area is completely obstructed by the road embankments.

c. Abutments are set back away from the main channel.

Case 2. Flow is confined to the main channel (i.e., there is no overbank flow). The normal river channel width becomes narrower due to the bridge itself or the bridge site is located at a narrowing reach of the river.

Case 3. A relief bridge in the overbank area with little or no bed material transport in the overbank area (i.e., clear-water scour).

Case 4. A relief bridge over a secondary stream in the overbank area with bed material transport (similar to case one).

Determination of Live-Bed or Clear-Water Contraction Scour

To determine if the flow upstream is transporting bed material (i.e., live-bed contraction scour), the program calculates the critical velocity for beginning of motion V_c (for the D_{50} size of bed material) and compares it with the mean velocity V of the flow in the main channel or overbank area upstream of the bridge at the approach section. If the critical velocity of the bed material is greater than the mean velocity at the approach section ($V_c > V$), then clear-water contraction scour is assumed. If the critical velocity of the bed material is less than the mean velocity at the approach section ($V_c < V$), then live-bed contraction scour is assumed. The user has the option of forcing the program to calculate contraction scour by the live-bed or clear-water contraction scour equation, regardless of the results from the comparison. To calculate the critical velocity, the following equation by Laursen (1963) is used:

$$V_c = 10.95\, y_1^{1/6}\, D_{50}^{1/3} \qquad (10\text{-}1)$$

Where: V_c = Critical velocity above which material of size D_{50} and smaller will be transported, ft/s (m/s)

y_1 = Average depth of flow in the main channel or overbank area at the approach section, ft (m)

D_{50} = Bed material particle size in a mixture of which 50% are smaller, ft (m)

Live-Bed Contraction Scour

The HEC No. 18 publication recommends using a modified version of Laursen's (1960) live-bed scour equation:

$$y_2 = y_1 \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{K_1} \qquad (10\text{-}2)$$

$$y_s = y_2 - y_0 \qquad (10\text{-}3)$$

Where: y_s = Average depth of contraction scour in feet (m).

y_2 = Average depth after scour in the contracted section, feet (m). This is taken as the section inside the bridge at the upstream end in HEC-RAS (section BU).

y_1 = Average depth in the main channel or floodplain at the approach section, feet (m).

y_0 = Average depth in the main channel or floodplain at the contracted section before scour, feet (m).

Q_1 = Flow in the main channel or floodplain at the approach section, which is transporting sediment, cfs (m^3/s).

Q_2 = Flow in the main channel or floodplain at the contracted section, which is transporting sediment, cfs (m^3/s).

W_1 = Bottom width in the main channel or floodplain at the approach section, feet (m). This is approximated as the top width of the active flow area in HEC-RAS.

W_2 = Bottom width of the main channel or floodplain at the contracted section less pier widths, feet (m). This is approximated as the top width of the active flow area.

k_1 = Exponent for mode of bed material transport.

V_* / ω	k_1	Mode of Bed Material Transport
< 0.50	0.59	Mostly contact bed material discharge
0.50 to 2.0	0.64	Some suspended bed material discharge
> 2.0	0.69	Mostly suspended bed material discharge

V_* = $(g\, y_1\, S_1)^{1/2}$, shear velocity in the main channel or floodplain at the approach section, ft/s (m/s).
ω = Fall velocity of bed material based on D_{50}, ft/s (m/s).
g = Acceleration of gravity, ft/s^2 (m/s^2).
S_1 = Slope of the energy grade line at the approach section, ft/ft (m/m).

Clear-Water Contraction Scour

The recommended clear-water contraction scour equation by the HEC No. 18 publication is an equation based on research from Laursen (1963):

$$y_2 = \left[\frac{Q_2^2}{C\, D_m^{2/3}\, W_2^2} \right]^{3/7} \tag{10-4}$$

$$y_s = y_2 - y_0 \tag{10-5}$$

Where D_m = Diameter of the smallest non-transportable particle in the bed material (1.25 D_{50}) in the contracted section, feet (m).
D_{50} = Median diameter of the bed material, feet (m).
C = 120 for English units (40 for metric).

Note: If the bridge opening has overbank area, then a separate contraction scour computation is made for the main channel and each of the overbanks.

Computing Local Scour at Piers

Pier scour occurs due to the acceleration of flow around the pier and the formation of flow vortices (known as the horseshoe vortex). The horseshoe vortex removes material from the base of the pier, creating a scour hole. As the depth of scour increases, the magnitude of the horshoe vortex decreases, thereby reducing the rate at which material is removed from the scour hole. Eventually an equilibrium between bed material inflow and outflow is reached, and the scour hole ceases to grow.

The factors that affect the depth of local scour at a pier are: velocity of the flow just upstream of the pier; depth of flow; width of the pier; length of the pier if skewed to the flow; size and gradation of bed material; angle of attack of approach flow; shape of the pier; bed configuration; and the formation of ice jams and debris.

The HEC No. 18 report recommends the use of the Colorado State University (CSU) equation (Richardson, 1990) for the computation of pier scour under both live-bed and clear-water conditions. The CSU equation is the default equation in the HEC-RAS software. In addition to the CSU equation, an equation developed by Dr. David Froehlich (1991) has also been added as an alternative pier scour equation. The Froehlich equation is not recommended in the HEC No. 18 report, but has been shown to compare well with observed data.

Computing Pier Scour With The CSU Equation

The CSU equation predicts maximum pier scour depths for both live-bed and clear-water pier scour. The equation is:

$$y_s = 2.0\, K_1\, K_2\, K_3\, K_4\, a^{0.65}\, y_1^{0.35}\, Fr_1^{0.43} \qquad (10\text{-}6)$$

Where: y_s = Depth of scour in feet (m)
K_1 = Correction factor for pier nose shape
K_2 = Correction factor for angle of attack of flow
K_3 = Correction factor for bed condition
K_4 = Correction factor for armoring of bed material
a = Pier width in feet (m)
y_1 = Flow depth directly upstream of the pier in feet (m). This is taken from the flow distribution output for the cross section just upstream from the bridge.
Fr_1 = Froude Number directly upstream of the pier. This is taken from the flow distribution output for the cross section just upstream from the bridge.

Note: For round nose piers aligned with the flow, the maximum scour depth is limited as follows:

$y_s \leq 2.4$ times the pier width (a) for $Fr_1 \leq 0.8$
$y_s \leq 3.0$ times the pier width (a) for $Fr_1 > 0.8$

The correction factor for pier nose shape, K_1, is given in Table 10.1 below:

Table 10.1
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) Group of cylinders	1.0
(e) Sharp nose (triangular)	0.9

The correction factor for angle of attack of the flow, K_2, is calculated in the program with the following equation:

$$K_2 = \left(\cos\theta + \frac{L}{a} \sin\theta \right)^{0.65} \tag{10-7}$$

Where: L = Length of the pier along the flow line, feet (m)
θ = Angle of attack of the flow, with respect to the pier

Note: If L/a is larger than 12, the program uses L/a = 12 as a maximum in equation 10-7. If the angle of attack is greater than 5 degrees, K_2 dominates and K_1 should be set to 1.0 (the software does this automatically).

The correction factor for bed condition, K_3, is shown in table 10.2.

Table 10.2
Increase in Equilibrium Pier Scour Depth, K_3, For Bed Condition

Bed Condition	**Dune Height H feet**	**K_3**
Clear-Water Scour	N/A	1.1
Plane Bed and Antidune Flow	N/A	1.1
Small Dunes	$10 > H \geq 2$	1.1
Medium Dunes	$30 > H \geq 10$	1.1 to 1.2
Large Dunes	H 30	1.3

The correction factor K_4 decreases scour depths for armoring of the scour hole for bed materials that have a D_{50} equal to or larger than 0.20 feet (0.06 m). The correction factor results from recent research by A. Molinas at CSU, which showed that when the velocity (V_1) is less than the critical velocity (V_{c90}) of the D_{90} size of the bed material, and there is a gradation in sizes in the bed material, the D_{90} will limit the scour depth. The equation developed by J. S. Jones from analysis of the data is:

$$K_4 = \left[1 - 0.89(1 - V_R)^2\right]^{0.5} \qquad (10\text{-}8)$$

Where:

$$V_R = \left[\frac{V_1 - V_i}{V_{c90} - V_i}\right] \qquad (10\text{-}9)$$

$$V_i = 0.645\left[\frac{D_{50}}{a}\right]^{0.053} V_{c50} \qquad (10\text{-}10)$$

V_R = Velocity ratio
V_1 = Average velocity in the main channel or overbank area at the cross section just upstream of the bridge, ft/s (m/s)
V_i = Velocity when particles at a pier begin to move, ft/s (m/s)
V_{c90} = Critical velocity for D_{90} bed material size, ft/s (m/s)
V_{c50} = Critical velocity for D_{50} bed material size, ft/s (m/s)
a = Pier width, ft (m)

$$V_c = 10.95\, Y^{1/6}\, D_c^{1/3} \tag{10-11}$$

Where: y = The depth of water just upstream of the pier, ft (m)
D_c = Critical particle size for critical velocity V_c, ft (m)

Limiting K_4 values and bed material size are given in Table 10.3.

Table 10.3
Limits for Bed Material Size and K_4 Values

Factor	Minimum Bed Material Size	Minimum K_4 Value	V_R > 1.0
K_4	$D_{50} \geq$ 0.2 ft (0.06 m)	0.7	1.0

Computing Pier Scour With The Froehlich Equation

A local pier scour equation developed by Dr. David Froehlich (Froehlich, 1991) has been added to the HEC-RAS software as an alternative to the CSU equation. This equation has been shown to compare well against observed data (FHWA, 1996). The equation is:

$$y_s = 0.32\phi\,(a')^{0.62}\, y_1^{0.47}\, Fr_1^{0.22}\, D_{50}^{-0.09} + a \tag{10-12}$$

where: ϕ = Correction factor for pier nose shape: ϕ = 1.3 for square nose piers; ϕ = 1.0 for rounded nose piers; and ϕ = 0.7 for sharp nose (triangular) piers.
a = Projected pier width with respect to the direction of the flow, feet (m)

Note: This form of Froehlich's equation is use to predict maximum pier scour for design purposes. The addition of one pier width (+ *a*) is placed in the equation as a factor of safety. If the equation is to be used in an analysis mode (i.e. for predicting the scour of a particular event), Froehlich suggests dropping the addition of the pier width (+ *a*). The HEC-RAS program always includes the addition of the pier width (+ *a)* when computing pier scour. The pier scour from this equation is limited to a maximum in the same manner as the CSU equation. Maximum scour $y_s \lesssim 2.4$ times the pier width (a) for $Fr_1 \lesssim 0.8$, and $y_s \lesssim 3.0$ times the pier width (a) for $Fr_1 > 0.8$.

Computing Local Scour at Abutments

Local scour occurs at abutments when the abutment obstructs the flow. The obstruction of the flow forms a horizontal vortex starting at the upstream end of the abutment and running along the toe of the abutment, and forms a vertical wake vortex at the downstream end of the abutment.

The HEC No. 18 report recommends two equations for the computation of live-bed abutment scour. When the wetted embankment length (L) divided by the approach flow depth (y_1) is greater than 25, the HEC No. 18 report suggests using the HIRE equation (Richardson, 1990). When the wetted embankment length divided by the approach depth is less than or equal to 25, the HEC No. 18 report suggests using an equation by Froehlich (Froehlich, 1989).

The HIRE Equation

The HIRE equation is based on field data of scour at the end of spurs in the Mississippi River (obtained by the USACE). The HIRE equation is:

$$y_s = 4\, y_1 \left(\frac{K_1}{0.55} \right) K_2\, Fr_1^{0.33} \qquad (10\text{-}13)$$

where: y_s = Scour depth in feet (m)

y_1 = Depth of flow at the toe of the abutment on the overbank or in the main channel, ft (m), taken at the cross section just upstream of the bridge.

K_1 = Correction factor for abutment shape, Table 10.4

K_2 = Correction factor for angle of attack (θ) of flow with abutment. $\theta = 90$ when abutments are perpendicular to the flow, $\theta < 90$ if embankment points downstream, and $\theta > 90$ if embankment points upstream.

Fr_1 = Froude number based on velocity and depth adjacent and just upstream of the abutment toe

Table 10.4
Correction Factor for Abutment Shape, K_1

Description	K_1
Vertical-wall Abutment	1.00
Vertical-wall Abutment with wing walls	0.82
Spill-through Abutment	0.55

The correction factor, K_2, for angle of attack can be taken from Figure 10.1.

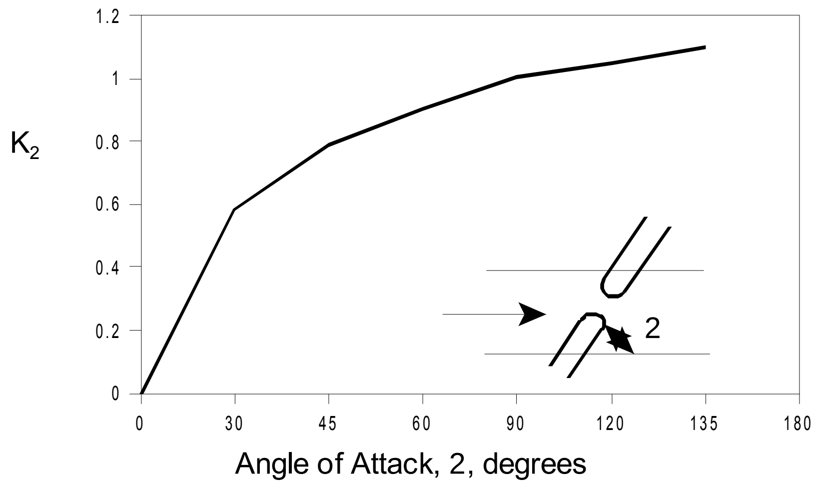

Figure 10.1 Correction Factor for Abutment Skew, K_2

Froehlich's Equation

Froehlich analyzed 170 live-bed scour measurements in laboratory flumes by regression analysis to obtain the following equation:

$$y_s = 2.27 K_1 K_2 (L')^{0.43} y_a^{0.57} Fr^{0.61} + y_a \quad (10\text{-}14)$$

where:
- y_s = Scour depth in feet (m)
- K_1 = Correction factor for abutment shape, Table 10.4
- K_2 = Correction factor for angle of attack (θ) of flow with abutment. θ = 90 when abutments are perpendicular to the flow, θ < 90 if embankment points downstream, and θ > 90 if embankment points upstream (Figure 10.1)
- L' = Length of abutment (embankment) projected normal to flow, ft (m)
- y_a = Average depth of flow on the floodplain at the approach section, ft (m)
- Fr = Froude number of the floodplain flow at the approach section, $Fr = V_e /(gy_a)^2$
- V_e = Average velocity of the approach flow $V_e = Q_e /A_e$ ft/s
- Q_e = Flow obstructed by the abutment and embankment at the approach section, cfs (m^3/s)
- A_e = Flow area of the approach section obstructed by the abutment and embankment, ft^2 (m^2)

Note: The above form of the Froehlich equation is for design purposes. The addition of the average depth at the approach section, y_a, was added to the equation in order to envelope 98 percent of the data. If the equation is to be used in an analysis mode (i.e. for predicting the scour of a particular event), Froehlich suggests dropping the addition of the approach depth ($+ y_a$). The HEC-RAS program always calculates the abutment scour with the ($+y_a$) included in the equation.

Clear-Water Scour at Abutments

Clear-water scour can be calculated with equation 9-13 or 9-14 for live-bed scour because clear-water scour equations potentially decrease scour at abutments due to the presence of coarser material. This decrease is unsubstantiated by field data.

Total Scour Depths Inside The Bridge

The total depth of scour is a combination of long-term bed elevation changes, contraction scour, and local scour at each individual pier and abutment. Once the scour is computed, the HEC-RAS software automatically plots the scour at the upstream bridge cross section. An example plot is shown in Figure 10.2 below.

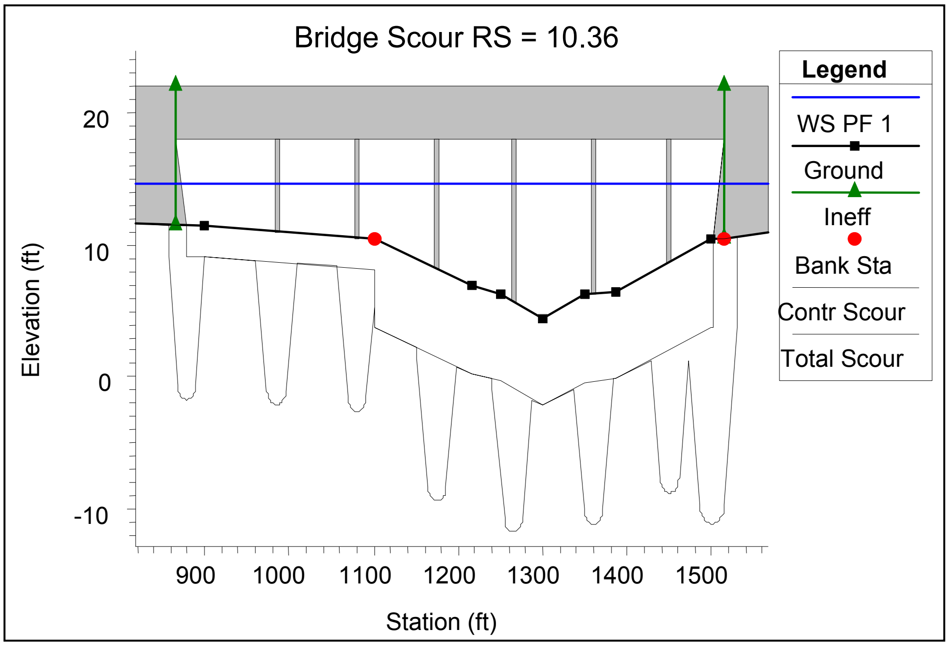

Figure 10.2 Graphic of Contraction and Total Scour at a Bridge

As shown in figure 10.2, the program plots both contraction scour and total local scour. The contraction scour is plotted as a separate line below the existing conditions cross section data. The local pier and abutment scour are added to the contraction scour, and then plotted as total scour depths. The topwidth of the local scour hole around a pier is computed as 2.0 y_s to each side of the pier. Therefore, the total topwidth of the scour hole at a pier is plotted as (4.0 y_s + a). The topwidth of the local scour hole at abutments is plotted as 2.0 y_s around each side of the abutment toe. Therefore, the total topwidth of the scour hole at abutments is plotted as 4.0 y_s.