# Scour Fundamentals and HEC-18

Scour is the leading cause of bridge failure over water, and it is invisible during the flood that causes it. This course covers the fundamentals of bridge scour as presented in FHWA Hydraulic Engineering Circular No. 18, Evaluating Scour at Bridges, 5th Edition (HEC-18, FHWA-HIF-12-003, 2012), with stream stability context from HEC-20, Stream Stability at Highway Structures, 4th Edition (FHWA-HIF-12-004, 2012). You will learn the components of total scour, the difference between clear-water and live-bed scour, how the HEC-18 contraction, pier and abutment equations are built, and how scour design and check floods are selected. Equations and table values are quoted from HEC-18 with section and equation numbers. Worked numbers not taken from an HEC-18 example are labeled illustrative.

**Learning objectives**

- Define the components of total scour
- Distinguish clear-water and live-bed scour
- Describe pier and abutment scour
- Select design and check floods

## Why scour matters

Scour is the erosion of streambed or bank material by flowing water, and at a bridge it removes the soil that supports foundations. HEC-18 Section 1.4.2 traces the national scour evaluation program to the April 1987 collapse of New York's Schoharie Creek Bridge, which failed because of scour. FHWA responded in 1988 with Technical Advisory T5140.20, which made scour evaluation an integral part of the National Bridge Inspection Standards. In 1991 it was superseded by T5140.23, "Evaluating Scour at Bridges," which gives guidance on four things:

1. Developing and implementing a scour evaluation for designing new bridges
2. Evaluating existing bridges for scour vulnerability
3. Using scour countermeasures
4. Improving the state of practice for estimating scour at bridges

HEC-18 is the procedure manual that implements that advisory. It is one of a family of FHWA hydraulic circulars that work together. HEC-20 covers stream stability and the geomorphic assessment that comes before any scour calculation. HEC-23 covers countermeasures. HDS 6 covers river engineering and sediment transport. This course concentrates on HEC-18, uses HEC-20 where stream behavior matters, and leaves plans of action and countermeasure design to BR-H02 and BR-H03.

Scour is hard to see. HEC-18 Section 3.4 explains that live-bed scour holes dug during the rising stage of a flood often refill on the falling stage. An inspector wading the channel a week later can find a smooth bed with no sign that the pier footing was undermined at the flood peak. That is why scour is evaluated by calculation and geomorphic judgment, not only by observation, and why the infilled material in a scour hole should not be counted on to support a foundation.

### Who does the work

HEC-18 Chapter 2 is emphatic that bridge foundations exposed to scour should be designed by an interdisciplinary team with hydraulic, geotechnical and structural expertise. The hydraulic engineer estimates the scour. The geotechnical engineer determines what the remaining soil or rock can carry. The structural engineer decides how the bridge behaves when support is

lost. A scour number handed over the wall without that conversation is a common source of either unsafe or wildly overconservative foundations.

## The components of total scour

HEC-18 Section 3.2 defines total scour at a highway crossing as the sum of three primary components:

1. **Long-term degradation** of the river bed
2. **Contraction scour** at the bridge
3. **Local scour** at the piers or abutments

The three are added to obtain total scour at a pier or abutment. HEC-18 notes that this assumes each component occurs independently of the others, and that treating them as additive adds some conservatism. On top of these, the evaluation must consider lateral migration of the stream and other scour types that occur in specific situations.

### Aggradation and degradation

Long-term bed elevation changes happen over reaches much longer than the bridge site. Aggradation is deposition of material eroded upstream; HEC-18 states plainly that aggradation is *not* considered a component of total scour. Degradation is lowering of the bed over long reaches because of a deficit in sediment supply, and it does count. Section 3.3 says long-term changes may be natural trends or the result of changes to the stream or watershed, and that a trend may change during the life of the bridge. Typical human causes include dams that trap sediment, channel straightening, gravel mining, and changes in land use. Because long-term change is a channel instability problem, HEC-18 points to HEC-20 for quantitative methods and to HDS 6 for sediment continuity.

### Contraction scour

Contraction scour (Section 3.2.2) is lowering of the bed across all or most of the channel width at the bridge, caused by a reduction in flow area. It differs from degradation because it occurs near the constriction, may be cyclic, and is related to the passing of a flood. Section 3.5 lists causes beyond the bridge itself: natural stream constrictions, long approach embankments over the floodplain, ice jams, natural berms, debris, vegetation, and pressure flow when the water reaches the superstructure.

### Local scour

Local scour (Section 3.2.3) is the removal of material from around piers, abutments, spurs and embankments, caused by flow acceleration and the vortices the obstruction creates. It is usually the deepest component at an individual pier.

### Other scour and lateral migration

Section 3.2.4 adds bend scour concentrated at the outside of a bend, scour from planform characteristics, scour at confluences, and scour caused by a variable downstream control. Section 3.2.5 adds lateral migration: a meandering main channel can move across its floodplain and reach piers that were designed as floodplain piers, erode abutments or approach roads, or change the angle of attack at piers. HEC-18 directs the designer to HEC-20 and HDS 6 for these assessments.

**Practical consequence:** a foundation evaluation that computes only local pier scour from the current bed elevation can be badly wrong if the channel is degrading, if the thalweg can migrate to that pier, or if contraction scour lowers the whole section first.

## Clear-water and live-bed scour

HEC-18 Section 3.4 distinguishes two conditions for both contraction and local scour.

- **Clear-water scour** occurs when there is no movement of bed material in the flow upstream of the crossing, or when material transported from upstream passes through in suspension at less than the capacity of the flow. Locally, the acceleration and vortices at the pier or abutment still move bed material there.
- **Live-bed scour** occurs when bed material is transported from the upstream reach into the crossing. Live-bed local scour is cyclic: the hole develops on the rising stage and refills on the falling stage.

HEC-18 lists typical clear-water situations: coarse-bed streams, flat-gradient streams at low flow, local deposits of material larger than the biggest fraction being transported (riprap is a special case), armored beds where only the pier or abutment vortices can penetrate the armor, and vegetated channels or overbanks.

### How scour develops in time

Clear-water scour reaches its maximum over a longer time than live-bed scour, and local clear-water scour may not reach its maximum until after several floods. HEC-18 states that maximum local clear-water pier scour is about 10 percent greater than equilibrium local live-bed pier scour. In live-bed conditions with a dune bed, scour fluctuates around equilibrium as dunes pass, and the maximum can be about 30 percent larger than equilibrium. Except on very large rivers such as the Mississippi or Columbia, sand beds plane out at flood flows, so for general practice HEC-18 takes maximum pier scour as about 10 percent greater than equilibrium. That is the origin of the $K_3$ bed condition factor discussed later.

### Deciding which condition applies

HEC-18 compares the mean upstream velocity V with the critical velocity $V_c$ for the median bed material size $D_{50}$. If $V \le V_c$, contraction and local scour will be clear-water. If $V > V_c$, live-bed scour will occur. Section 3.4 adds that if the ratio of shear velocity to the fall velocity of $D_{50}$ ($V_*/\omega$) is greater than 2, scour may be clear-water. The critical velocity equation (HEC-18 Eq. 6.1) is:

$$\mathbf{V_c = K_u\, y^{1/6}\, D^{1/3}}, \text{ with } K_u = 11.17 \text{ (U.S. customary) or } 6.19 \text{ (SI)}$$

where y is the average upstream flow depth and D is the particle size. HEC-18 takes $D_{50}$ as the average bed material size in the upper 1 ft of the bed upstream of the bridge, and notes a reasonable lower limit of $D_{50}$ = 0.2 mm because cohesion tends to raise the critical velocity of finer material.

**Illustrative example (not from HEC-18):** for an upstream depth of 8 ft and $D_{50}$ = 2 mm (0.00656 ft), $V_c = 11.17 \times 8^{1/6} \times 0.00656^{1/3} \approx 2.96$ ft/s. If the main-channel velocity at the scour design flood is 6 ft/s, the channel is live-bed. If the vegetated overbank carries 1.5 ft/s, the overbank is clear-water. HEC-18 cautions that the procedure should be used with care on overbanks, where vegetation binds the surface and most overbank areas experience clear-water scour.

## Selecting the scour design and check floods

HEC-18 Chapter 2 changed the 5th Edition's flood selection to a risk-based approach. Previously, all bridges were designed for scour using the $Q_{100}$ flood and checked with the $Q_{500}$. Table 2.1 now ties the scour floods to the hydraulic design flood:

| Hydraulic design flood, $Q_D$ | Scour design flood, $Q_S$ | Scour design check flood, $Q_C$ |
|---|---|---|
| Q10 | Q25 | Q50 |
| Q25 | Q50 | Q100 |
| Q50 | Q100 | Q200 |
| Q100 | Q200 | Q500 |

The reasoning is about exceedance probability. HEC-18 notes that over a 50-year design life there is a 39.5 percent chance that a bridge designed to pass $Q_{100}$ will see that flood or a larger one, a 63.6 percent chance for $Q_{50}$, and a 22.2 percent chance for $Q_{200}$. Designing for scour at a higher level than the hydraulic design matters because if the hydraulic design flood is exceeded, more scour will occur. The check flood is a further step up for the same reason.

The general expression behind those numbers is $P = 1 - (1 - 1/T)^n$, where T is the return period and n is the number of years. *Illustrative:* for a 75-year service life the same formula gives about 53 percent for $Q_{100}$ and about 31 percent for $Q_{200}$, which is why longer design lives argue for conservative scour floods.

### Overtopping and worse intermediate floods

HEC-18 adds an important rule. If a flood larger than the hydraulic design flood but smaller than the scour design flood causes greater stress on the bridge, such as an overtopping flood, it becomes the scour design flood, and there is no separate check flood. Likewise, a flood between the scour design and check floods that causes greater stress becomes the check flood. Overtopping matters because it can produce pressure flow and the highest velocities through the opening at a discharge below the peak.

### The general design procedure

HEC-18 Section 2.2 gives six steps for setting substructure type, size and location:

1. Select the flood events expected to produce appropriately severe scour (Table 2.1, adjusted for overtopping).
2. Develop hydraulic parameters with a one- or two-dimensional model. HEC-18 recommends HEC-RAS for 1D work and a 2D model for complex sites such as skewed embankments, multiple openings, wide floodplains or highly contracted flow.
3. Estimate total scour using the specific design approach in Section 2.4, and apply commonly accepted geotechnical safety factors to the foundation design for that condition.
4. Plot total scour depths on a cross section of the channel and floodplain.
5. Evaluate the results for reasonableness with the interdisciplinary team. The adopted depths may differ from computed values based on storm duration, erodibility, ice, debris and other factors.
6. Evaluate and modify the bridge size, configuration and foundations. HEC-18's list of ways to reduce scour starts with increasing bridge length, which lowers flow depth and velocity through the opening.

## Contraction scour: the four cases

HEC-18 Chapter 6 explains contraction scour through continuity. When the flow area is reduced, average velocity and bed shear stress rise, more material leaves the contracted reach than enters it, and the bed lowers. As the bed lowers, the area increases and, in a riverine setting, velocity and shear fall until equilibrium is reached. Either the sediment transported in equals the sediment carried out (live-bed), or shear falls to the point that nothing moves (clear-water).

HEC-18 Section 3.5 notes that in tidal waterways this self-limiting behavior may not hold, because as the cross section grows the discharge from the ocean can grow too. Contraction scour at tidal inlets may continue to lower the bed. Tidal scour is treated in HEC-18 Chapter 9 and HEC-25.

### The four cases

HEC-18 Section 6.2.2 describes four commonly encountered cases:

- **Case 1**: overbank flow on a floodplain forced back to the main channel by the bridge approaches. It has three variants: (a) the channel narrows because abutments project into it or the bridge is at a narrow reach; (b) no main-channel contraction, but the overbank flow is completely obstructed by an embankment; (c) abutments set back from the channel.
- **Case 2**: flow confined to the main channel with no overbank flow, and the channel narrows because of the bridge or a natural narrowing.
- **Case 3**: a relief bridge in the overbank with little or no bed material transport (clear-water).
- **Case 4**: a relief bridge over a secondary stream in the overbank with bed material transport (similar to Case 1).

Cases 1, 2 and 4 may be live-bed or clear-water depending on whether bed material is transported into the bridge reach. HEC-18 calls Case 1c very complex: the main channel may be live-bed while the set-back overbank is clear-water, and the result depends on setback distance, overbank erodibility and vegetation, and how much overbank flow returns to the opening. The engineer needs only to decide whether each part of the opening receives bed material, then apply the live-bed or clear-water equation with variables defined for that location. HEC-18 Note 8 adds that where coarse sediments may armor the bed, live-bed contraction scour should also be computed with the clear-water equation and the smaller depth used.

### Why the overbank matters

Section 3.5 explains that approach embankments cutting off floodplain flow cause clear-water scour on setback portions of the bridge opening or at relief bridges, because floodplain flow does not normally carry much bed sediment. That clear water picks up sediment when it reaches the opening. Local scour at abutments may also be greater because the clear-water floodplain flow returns to the main channel at the end of the abutment.

## Live-bed and clear-water contraction equations

### Live-bed: modified Laursen equation

HEC-18 recommends a modified version of Laursen's 1960 equation for live-bed scour at a long contraction (Eq. 6.2 and 6.3):

$$\mathbf{y_2/y_1 = (Q_2/Q_1)^{6/7}\,(W_1/W_2)^{k1}}, \text{ and } \mathbf{y_s = y_2 - y_o}$$

- $y_1$ = average depth in the upstream main channel; $y_2$ = average depth in the contracted section after scour; $y_o$ = existing depth in the contracted section before scour
- $Q_1$ = flow in the upstream main channel transporting sediment (not including overbank flow); $Q_2$ = flow in the contracted channel
- $W_1$ = bottom width of the upstream main channel transporting bed material; $W_2$ = bottom width of the main channel in the contracted section less pier widths
- $k_1$ depends on $V_*/\omega$: 0.59 for <0.50 (mostly contact bed load), 0.64 for 0.50 to 2.0 (some suspended), 0.69 for >2.0 (mostly suspended)

$V_* = (g\ y_1\ S_1)^{1/2}$ is the shear velocity upstream and ω is the fall velocity of $D_{50}$. The modification is the removal of Laursen's Manning n ratio. HEC-18 also warns that Laursen's equation will overestimate scour if the bridge is located at the upstream end of a natural contraction or if the contraction is the result of the bridge abutments and piers, though at this time it is the best equation available. Where coarse sediments are present it recommends computing live-bed scour with the clear-water equation as well where coarse sediments may armor the bed, and using the smaller result.

**Illustrative example (not from HEC-18):** embankments return overbank flow so that $Q_2/Q_1 = 1.3$, the channel width does not change ($W_1/W_2 = 1.0$), $y_1 = 8$ ft and $y_o = 8$ ft. Then $y_2 = 8 \times 1.3^{6/7} \approx 8 \times 1.252 \approx 10.0$ ft, and $y_s \approx 2.0$ ft of live-bed contraction scour across the channel.

### Clear-water: Laursen 1963 development

For clear-water contraction scour HEC-18 gives Eq. 6.4 and 6.5:

$\mathbf{y_2 = [K_u\ Q^2 / (D_m^{2/3}\ W^2)]^{3/7}}$, and $\mathbf{y_s = y_2 - y_o}$

- $K_u = 0.0077$ (U.S. customary) or 0.025 (SI)
- Q = discharge through the bridge or on the set-back overbank associated with width W
- $D_m$ = diameter of the smallest nontransportable particle, taken as 1.25 $D_{50}$
- W = bottom width of the contracted section less pier widths

The equation is a rearranged form of the critical velocity relationship: the bed lowers until the velocity in the contracted section equals the critical velocity of $D_m$. The 1.25 factor reflects slight armoring because $D_{50}$ is not the largest particle present. For stratified bed material HEC-18 says to apply the equation sequentially with the $D_m$ of each layer. The 0.2 mm lower limit on $D_{50}$ applies here too; HEC-18 says using a smaller size will overestimate clear-water contraction scour.

**Illustrative example (not from HEC-18):** Q = 10,000 cfs through a 200 ft bottom width, $D_{50} = 2$ mm, so $D_m = 2.5$ mm = 0.0082 ft. $y_2 = [0.0077 \times 10{,}000^2 / (0.0082^{2/3} \times 200^2)]^{3/7} \approx 14.0$ ft. If the existing average depth is 10 ft, $y_s \approx 4.0$ ft. Check units carefully: every length in this equation is in feet, including $D_m$.

HEC-18 Section 6.8 and Section 6.9 address contraction scour in erodible rock and at open-bottom culverts. Rock and cohesive soils are not handled with the sand-based equations above; they need the erodibility-based approaches in HEC-18 Chapters 4 and 6, normally with geotechnical testing.

## Local scour mechanics at piers

HEC-18 Section 3.6 explains the mechanism. Water piles up on the upstream face of a pier and accelerates around its nose, forming a **horseshoe vortex** at the base that removes bed material. As the hole deepens, the vortex weakens. In live-bed conditions scouring stops when inflow and outflow of sediment balance; in clear-water conditions it stops when the vortex shear equals the critical shear of the particles at the bottom of the hole. Vertical **wake vortices** downstream also remove material, but their intensity falls off quickly, so there is often deposition immediately downstream of a long pier.

### Factors that control local scour

HEC-18 lists ten factors and explains several of them:

- **Velocity**: the greater the velocity, the deeper the scour. Most research is for subcritical flow (Froude number < 1).
- **Flow depth**: an increase in depth can increase pier scour by a factor of 2 or more.
- **Pier width**: scour increases with width, up to a limit. Very wide piers do not scour as deeply as the basic equations predict.
- **Pier length**: no appreciable effect when aligned with the flow, but when skewed, doubling the length increases scour by 30 to 60 percent depending on the angle of attack.
- **Bed material**: sand-size material has little effect on depth. Coarse gravels, cobbles and boulders may armor the hole. Silts and clays scour as deep as sand, even when cohesive; cohesion mainly lengthens the time to reach maximum, which in sand is measured in hours and in cohesive soils may take many floods.
- **Angle of attack**: has a significant effect at piers and abutments.
- **Nose shape**: up to a 20 percent influence. A square nose scours about 20 percent deeper than a sharp nose and 10 percent deeper than a round nose or cylinder. Shape is negligible for angles over 5 degrees.
- **Bed configuration**, and **ice and debris**, which effectively widen the pier.

These factors explain why field observations sometimes disagree with simple expectations. A pier that was aligned with the channel at construction can see a large angle of attack after the channel migrates, and a debris raft can turn a 3 ft column into a much wider obstruction during a flood.

## The HEC-18 pier scour equation

HEC-18 Section 7.2 recommends the HEC-18 equation, based on the Colorado State University (CSU) equation, for both live-bed and clear-water pier scour. It predicts maximum pier scour depth (Eq. 7.1):

$$\mathbf{y_s/y_1 = 2.0\, K_1\, K_2\, K_3\, (a/y_1)^{0.65}\, Fr_1^{0.43}}$$

- $y_s$ = scour depth; $y_1$ = flow depth directly upstream of the pier; a = pier width; L = pier length
- $Fr_1 = V_1/(g\, y_1)^{1/2}$, the Froude number directly upstream of the pier
- $K_1$ = nose shape factor (Table 7.1): square nose 1.1; round nose 1.0; circular cylinder 1.0; group of cylinders 1.0; sharp nose 0.9
- $K_2$ = angle of attack factor, $K_2 = (\cos\theta + (L/a)\sin\theta)^{0.65}$ (Eq. 7.4), with L/a capped at 12
- $K_3$ = bed condition factor (Table 7.3): 1.1 for clear-water, plane bed, antidunes and small dunes; 1.2 to 1.1 for medium dunes; 1.3 for large dunes

HEC-18 gives a rule of thumb for round-nose piers aligned with the flow: $y_s \le 2.4a$ for $Fr \le 0.8$ and $y_s \le 3.0a$ for $Fr > 0.8$.

### Notes that change the answer

- Use $K_1$ from Table 7.1 only for angles of attack up to 5 degrees. For larger angles $K_2$ dominates and $K_1$ is taken as 1.0.
- $K_2$ applies only if the entire pier length is subjected to the angle of attack. If part of the pier is shielded by an abutment or another pier, or if flow is redirected parallel to the pier, judgment is used to select an effective length. Table 7.2 illustrates the effect and sets a cutoff of $K_2 = 5.0$.
- $K_3$ reflects the observation that for plane-bed conditions, typical of most sites at scour design floods, maximum scour may be 10 percent greater than the equation; large dunes on very large rivers may give 30 percent.

- Piers close to abutments, such as at the toe of a spill-through slope, must be evaluated carefully for the angle and velocity of flow coming around the abutment.

### HEC-18 Example Problems 1 and 2

HEC-18 Section 7.10.1 works a round-nose pier with a = 4.0 ft, L = 59 ft, $y_1$ = 10.2 ft, $V_1$ = 11.02 ft/s, zero angle of attack and plane bed. Fr = 0.61. With $K_1$ = 1.0, $K_2$ = 1.0, $K_3$ = 1.1, $y_s/y_1$ = 0.97 and $y_s$ = 9.9 ft. The rule-of-thumb check gives 2.4 × 4.0 = 9.6 ft. Example Problem 2 uses a 20 degree angle of attack. L/a = 14.8, which exceeds 12, so 12 is used: $K_2 = (\cos 20° + 12 \sin 20°)^{0.65} = 2.86$, and $y_s = 9.9 \times 2.86 = 28.3$ ft. A 20 degree skew nearly triples the scour, which is the single most important lesson of the pier equation.

**Illustrative example (not from HEC-18):** a 3 ft wide round-nose wall pier, L/a = 8, $y_1$ = 12 ft, $V_1$ = 8 ft/s, plane bed. $Fr = 8/(32.2 \times 12)^{1/2} \approx 0.41$. $y_s = 12 \times 2.0 \times 1.0 \times 1.0 \times 1.1 \times (3/12)^{0.65} \times 0.41^{0.43} \approx 7.3$ ft, close to the 2.4a = 7.2 ft rule of thumb. If a meander shift puts the flow at 15 degrees, $K_2 = (\cos 15° + 8 \sin 15°)^{0.65} \approx 2.06$ and $y_s \approx 15$ ft.

### Complex piers, wide piers and alternatives

HEC-18 adapts the basic equation for wide piers in shallow flow with a $K_w$ factor (Section 7.4), for complex piers made of a stem, pile cap or footing and pile group by superposing three components (Section 7.5), for multiple columns skewed to the flow (Section 7.6), and for debris on piers (Section 7.7). In Example Problem 3 a 4 ft pier on an 8 ft wide footing exposed by degradation gives a total local pier scour of 15.4 ft, most of it (14.8 ft) from the exposed footing. Example Problem 4 applies the method to a complex pier tested in physical models for the Woodrow Wilson Bridge. HEC-18 Section 7.3 also presents the Florida DOT pier scour methodology as an alternative; it cites an NCHRP study of 22 pier scour equations in which the HEC-18 equation did well but the Sheppard and Miller (2006) equation generally performed better. Section 7.9 recommends physical model studies for unusual or complex foundations.

HEC-18 Section 7.8 estimates the topwidth of a pier scour hole in cohesionless material from each side of the pier as between 1.0 and 2.8 $y_s$, and suggests 2.0 $y_s$ for practical applications. That width matters when deciding whether adjacent piers' scour holes overlap and how far riprap or other protection must extend.

## Abutment scour

HEC-18 Chapter 8 opens with the documented causes of abutment failure seen in post-flood inspections: overtopping of abutments or approach embankments, lateral channel migration or stream widening, contraction scour, and local scour at one or both abutments. Damage is often a combination. As a general rule the most vulnerable abutments are those at or near the channel banks. Where abutments are set back on wide floodplains, local scour holes as deep as four times the approach floodplain flow depth have been observed.

The flow obstructed by the abutment and embankment accelerates and forms a vortex at the upstream end of the abutment running along its toe, and a wake vortex forms at the downstream end. HEC-18 also warns about conditions that are hard to foresee on wide floodplains: gravel pits that capture the flow and divert the main channel, levee failures, and debris that creates adverse angles of attack.

## Why abutment equations are uncertain

Classic abutment equations (Liu, Laursen, Froehlich, Melville) are based entirely on laboratory data, and little field data exist. In a flume, the discharge intercepted by an abutment is directly tied to its length; in the field it rarely is, because the outer floodplain carries little "ineffective" flow. HEC-18 Section 8.2.2 therefore requires that equations using embankment length use L′, the length blocking *live* flow, found from a plot of conveyance versus distance across an upstream cross section.

## Shape and skew

HEC-18 Table 8.1 gives abutment shape coefficients: vertical-wall abutment 1.00; vertical wall with wing walls 0.82; spill-through 0.55. Scour at a vertical wall is roughly double that at a spill-through abutment. For skew, Section 3.6 reports Ahmad's (1953) finding that an embankment inclined 45 degrees downstream reduces maximum scour by 20 percent, while 45 degrees upstream increases it about 10 percent.

## Froehlich's equation

Froehlich analyzed 170 live-bed laboratory measurements to obtain HEC-18 Eq. 8.1:

$$\mathbf{y_s/y_a = 2.27\ K_1\ K_2\ (L'/y_a)^{0.43}\ Fr^{0.61} + 1}$$

where $K_1$ is the shape coefficient, $K_2 = (\theta/90)^{0.13}$ for embankment angle $\theta$ (less than 90 degrees if pointing downstream), $y_a$ is the average floodplain flow depth, and $Fr = V_e/(g\ y_a)^{1/2}$ with $V_e = Q_e/A_e$ for the obstructed flow. HEC-18 notes that the "+1" was added to envelope 98 percent of the data, which is why the equation does not go to zero as L′ goes to zero.

**Illustrative example (not from HEC-18):** spill-through abutment ($K_1 = 0.55$), perpendicular embankment ($K_2 = 1.0$), $L' = 300$ ft, $y_a = 4$ ft, $V_e = 2$ ft/s. $Fr = 2/(32.2 \times 4)^{1/2} \approx 0.18$. $y_s/y_a = 2.27 \times 0.55 \times (75)^{0.43} \times 0.18^{0.61} + 1 \approx 2.76 + 1 = 3.76$, so $y_s \approx 15$ ft. Numbers of this size are common with Froehlich's equation and are one reason HEC-18 treats abutment equations as guides.

## HIRE equation

The HIRE equation (Eq. 8.2), from USACE field data at the ends of spurs on the Mississippi River, applies when the ratio of projected abutment length to flow depth exceeds 25: $\mathbf{y_s/y_1 = 4\ Fr^{0.33}\ (K_1/0.55)\ K_2}$, with $y_1$ and Fr taken adjacent to and upstream of the abutment.

## NCHRP 24-20 approach

HEC-18 Section 8.6.3 presents the NCHRP 24-20 method. It starts from contraction scour and applies a factor for the large-scale turbulence near the abutment, rather than adding contraction scour to a separately computed abutment scour. It recognizes that flow concentrates near the abutment, so the contraction component there is larger than the average across the opening, and it distinguishes abutments in or near the main channel, set back from it, and cases where the embankment itself fails. The related NCHRP 2011 evaluation recommended minimum setbacks from the main channel bank with riprap protection and an apron sized per HEC-23, and two-dimensional models on all but the simplest crossings. HEC-18 concludes that abutment foundations should be designed to be safe from long-term degradation, lateral migration and contraction scour, and protected from local scour with countermeasures such as riprap, guide banks or dikes.

## Special materials: coarse beds, cohesive soils and rock

The sand-based equations above are the core of HEC-18, but the manual treats other materials separately.

- **Coarse bed material** (Section 7.11): prior editions used a $K_4$ armoring factor. The 5th Edition adds an FHWA coarse-bed pier scour equation (Eq. 7.34) based on laboratory data from the FHWA J. Sterling Jones Hydraulics Research Laboratory and USGS field data. It applies only to clear-water conditions with $D_{50} \geq 20$ mm and gradation coefficient $\sigma = D_{84}/D_{50} \geq 1.5$, and uses a densimetric particle Froude number.
- **Cohesive materials** (Section 7.12): HEC-18 notes that silts and clays can eventually scour as deep as sand, but over many floods rather than hours. Time-rate methods based on erosion testing of site soils can account for that.
- **Rock** (Section 6.8 and Chapter 4): erodible rock is evaluated with methods that consider the rock's resistance, not the sand equations, and massive rock with few discontinuities is described in Section 3.1 as highly resistant to scour over a bridge's life.

The practical point for engineers is that sand-equation results applied to stiff clay or weathered rock can be far too conservative, while assuming that "rock" or "clay" means no scour can be dangerous. These materials need geotechnical sampling and testing, and the interdisciplinary review that HEC-18 Chapter 2 calls for.

## Stream stability first: HEC-20

HEC-20 frames every scour evaluation inside a stream stability assessment, because degradation, lateral migration and changes in planform drive the inputs to HEC-18. HEC-20 describes three levels of analysis:

- **Level 1**: application of simple geomorphic concepts and other qualitative analyses
- **Level 2**: application of basic hydrologic, hydraulic and sediment transport engineering concepts
- **Level 3**: application of mathematical or physical modeling studies

HEC-20 states that a Level 1 qualitative analysis is a prerequisite for a Level 2 engineering analysis for bridge design, evaluation or rehabilitation. Its six Level 1 steps are: (1) define stream characteristics, (2) evaluate land use changes, (3) assess overall stream stability, (4) evaluate lateral stability, (5) evaluate vertical stability, and (6) evaluate channel response to change. The eight Level 2 steps cover flood history and rainfall-runoff, hydraulic conditions, bed and bank materials, watershed sediment yield, incipient motion, armoring potential, rating curve shifts, and scour conditions.

### The Lane relationship

HEC-20 uses Lane's proportional relationship, $\mathbf{Q\ S \propto Q_s\ D_{50}}$, where Q is water discharge, S is slope, $Q_s$ is sediment discharge and $D_{50}$ is median sediment size. It is a qualitative tool: if one side changes, the channel adjusts to restore the balance. HEC-20 gives examples. A degrading main stream causes its tributaries to degrade, and their extra sediment can slow or reverse the main-stream degradation. Reducing sediment supply, by watershed changes, upstream gravel mining or a dam, tends to cause degradation downstream. HEC-20 calls the relationship only an initial step, but a useful one because it warns of future problems.

HEC-20 also quotes Lane (1955) on planform: a sand-bed channel tends to meander where $S\ Q^{0.25} \leq 0.0017$ (U.S. customary, with Q the mean annual discharge). Planform and its tendency to change tell you which piers may someday be in the thalweg.

## Putting it together on a real bridge

A complete scour evaluation for a new or existing bridge follows a sequence that combines HEC-20 and HEC-18:

1. **Stream stability (HEC-20 Level 1, and Level 2 if needed).** Is the bed degrading or aggrading? Is the channel migrating? What has changed in the watershed?
2. **Hydrology and hydraulics.** Select the scour design and check floods from HEC-18 Table 2.1, including any overtopping flood that controls. Run a 1D or 2D model for depths and velocities at each substructure unit and in each part of the opening.
3. **Long-term change.** Estimate degradation over the bridge's life and apply it to the bed before computing other components.
4. **Contraction scour.** Classify the case and decide live-bed or clear-water for the main channel and each overbank; compute with Eq. 6.2 or 6.4.
5. **Local scour.** Pier scour with Eq. 7.1 (or the FDOT method), including realistic angles of attack and debris; abutment scour with Froehlich, HIRE or NCHRP 24-20.
6. **Total scour and reasonableness.** Add the components, plot the prism on the cross section, and review it with geotechnical and structural engineers.
7. **Foundation design or evaluation.** New foundations are designed to resist the design flood scour with normal safety factors and checked for the check flood. Existing foundations are compared with the computed scour to decide whether the bridge is scour critical.

For existing bridges, HEC-18 and FHWA guidance lead to the scour critical determination and a plan of action, covered in BR-H02. Underwater inspection of substructures is covered in BR-I09, and countermeasures in BR-H03.

### What inspectors and rating engineers should take from HEC-18

- A smooth bed after a flood does not mean no scour happened; live-bed holes refill.
- Skew is the biggest multiplier at long wall piers. Record the angle of the flow relative to each pier and any change since the last inspection.
- Debris effectively widens piers. Report its size and location.
- Exposed footings and pile caps change the pier scour problem; HEC-18 Example Problem 3 shows the footing dominating total local scour.
- Abutments near the bank and embankments that intercept large floodplain flow are the highest-risk abutment locations.
- Channel cross sections compared over time are the best evidence of degradation and migration.

## Summary

HEC-18 defines total scour as long-term degradation plus contraction scour plus local scour, with lateral migration and other scour types considered on top. Whether scour is clear-water or live-bed is decided by comparing approach velocity with the critical velocity of $D_{50}$. Contraction scour uses the modified Laursen live-bed equation or the clear-water equation with $D_m = 1.25\ D_{50}$. Pier scour uses the CSU-based HEC-18 equation with nose shape, angle of attack and bed condition factors, and the angle of attack can nearly triple the result. Abutment scour equations are laboratory-based and uncertain, which is why L′, setbacks, riprap aprons and 2D modeling matter. The 5th Edition selects scour design and check floods from the hydraulic design flood rather than always using $Q_{100}$ and $Q_{500}$, and any overtopping flood that controls is used instead. HEC-20's stream stability assessment comes first, because it supplies the long-term and lateral changes that make the scour prism realistic.

## Common errors in scour calculations

Most bad scour numbers come from the inputs, not the equations. The following checklist is drawn from the HEC-18 notes discussed in this course.

- **Wrong velocity and depth.** Eq. 7.1 uses depth and velocity directly upstream of the pier, not cross-section averages. In a 1D model, use the flow distribution output or a 2D model to get local values at each pier, especially for piers in the thalweg.
- **Ignoring future channel position.** If the channel can migrate, HEC-18 Section 3.2.5 means floodplain piers may someday see main-channel depths and velocities. Many agencies compute pier scour as if the thalweg were at every pier.
- **Applying $K_2$ to the whole pier when part is shielded.** HEC-18 Note 2 to Table 7.3 says this significantly overpredicts scour; use an effective length with judgment.
- **Using $K_1$ for skewed flow.** Above 5 degrees, $K_1 = 1.0$.
- **Mixing top and bottom widths.** HEC-18 Note 4 for Eq. 6.2 says $W_1$ and $W_2$ may be top or bottom widths, but they must be consistent, and $W_2$ excludes pier widths.
- **Using total flow for $Q_1$.** In Eq. 6.2, $Q_1$ is the upstream main-channel flow only, not including overbank flow.
- **Too fine a $D_{50}$.** HEC-18 sets a reasonable lower limit of 0.2 mm in the critical velocity and clear-water equations.
- **Unit errors.** Particle sizes in millimeters must be converted to feet in U.S. customary equations (1 mm = 0.00328 ft), and the $K_u$ constants differ between unit systems.
- **Using the full embankment length.** Abutment equations need L′, the length blocking live flow.
- **Stopping at the number.** HEC-18 Step 5 requires an interdisciplinary reasonableness review; adopted depths may differ from computed values.

## Data checklist for a scour evaluation

Before running any equation, assemble the data that HEC-18 and HEC-20 rely on. This list is a practical summary, not a quotation of either manual.

- Historical and current channel cross sections at the bridge, including inspection soundings, to show degradation or migration
- Bed material samples for $D_{50}$ and $D_{84}$, and borings showing soil or rock layers below the bed
- Foundation type, footing or pile tip elevations, and as-built drawings; HEC-18 references NCHRP work on bridges with unknown foundations
- Flood frequency discharges for the design, scour design and check floods, plus the overtopping discharge
- A hydraulic model with flow distribution between channel and overbanks
- Pier dimensions, nose shape, alignment to flow and debris history
- Watershed changes: dams, mining, urbanization, channelization (HEC-20 Level 1 Step 2)

## Key takeaways

- Total scour = long-term degradation + contraction scour + local scour; aggradation is not a component.
- Clear-water vs live-bed is decided by V vs Vc = 11.17 y^(1/6) D^(1/3) (U.S. units) for D50.
- Live-bed holes refill on the falling stage, so post-flood beds can hide maximum scour.

- HEC-18 Table 2.1 sets scour design and check floods one and two steps above the hydraulic design flood; a controlling overtopping flood governs.
- Pier scour: ys/y1 = 2.0 K1 K2 K3 (a/y1)^0.65 Fr^0.43; K2 for skew can nearly triple scour.
- Abutment equations are lab-based; use L′ for live flow and design abutments with setbacks and countermeasures.
- Do a HEC-20 stream stability assessment before computing scour.

## References


1. FHWA, HEC-18 Evaluating Scour at Bridges, 5th Edition, FHWA-HIF-12-003, 2012
2. FHWA, HEC-20 Stream Stability at Highway Structures, 4th Edition, FHWA-HIF-12-004, 2012
3. FHWA Technical Advisory T5140.23, Evaluating Scour at Bridges, 1991 (as summarized in HEC-18 Section 1.4.2).


Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.