



सत्यमेव जयते

GOVERNMENT OF INDIA
MINISTRY OF RAILWAYS

**Scour Depth Estimation, Countermeasures and
Monitoring at Bridge Crossings:
Guide for Engineers**

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Scour Depth Estimation, Countermeasures and Monitoring at Bridge Crossings: Guide for Engineers

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Scour Depth Estimation at Bridge Crossings

1.1 Scour at Bridge Piers

Scour is a natural phenomenon of lowering the riverbed level due to removal of sediment by the erosive action of flowing stream. The magnitude of reduction in the riverbed level below an assumed natural level (or initial level) is termed *scour depth*.

Contraction scour is the scour of streambed arising from accelerated flow through contraction of waterways, where flows over flood plains are converged by bridge causeways and channelled through the bridge waterways.

In contrast, *local scour* is developed near the structures (bridge piers) due to modification of the flow field as a result of obstruction to the flow by the structures.

Local scour is classified as clear-water scour and live-bed scour. *Clear-water scour* occurs when the sediment is removed from the scour hole but not supplied by the approaching flow. The equilibrium of scour is reached when the flow induced force can no longer dislodge the sediment particles from the scour hole. On the other hand, *live-bed scour*, occurs when the scour hole is continuously fed with the sediment by the approaching flow. The equilibrium of scour is attained over a period of time, when the rate of removal of sediment out of the scour hole equals the rate of supply of sediment into the scour hole. Usually, the magnitude of scour depth in live-bed is to some extent less than that in clear-water, if the flow condition is such that the approaching flow velocity U equals or is slightly less the threshold flow velocity U_{cr} for the bed sediment motion.



Fig. 1.1 Scour taking place at bridge piers in a field condition

At bridge sites, local scour in the vicinity of piers, over which the bridge superstructure rests, poses a challenging problem to the civil engineers. Fig. 1.1 shows the photograph of bridge piers, where the scour takes place even in the summer season at a lean flow discharge condition. Failure of bridges due to scour at pier foundations is a common occurrence, if the magnitude of scour is too large to uncover the pier foundations. The obstruction to the approaching flowing stream by a bridge pier causes a three-dimensional separation of flow forming a vortex flow and a periodical vortex shedding downstream of the pier. The flow separates at the upstream face of the pier as it travels by the side of the pier, creating a vortex trail, termed *horseshoe vortex*, which moves downstream. As a result of which local scour

takes place around the pier due to the removal of bed sediment. Fig. 1.2 shows the photograph of an equilibrium scour at a circular pier in an experimental flume.

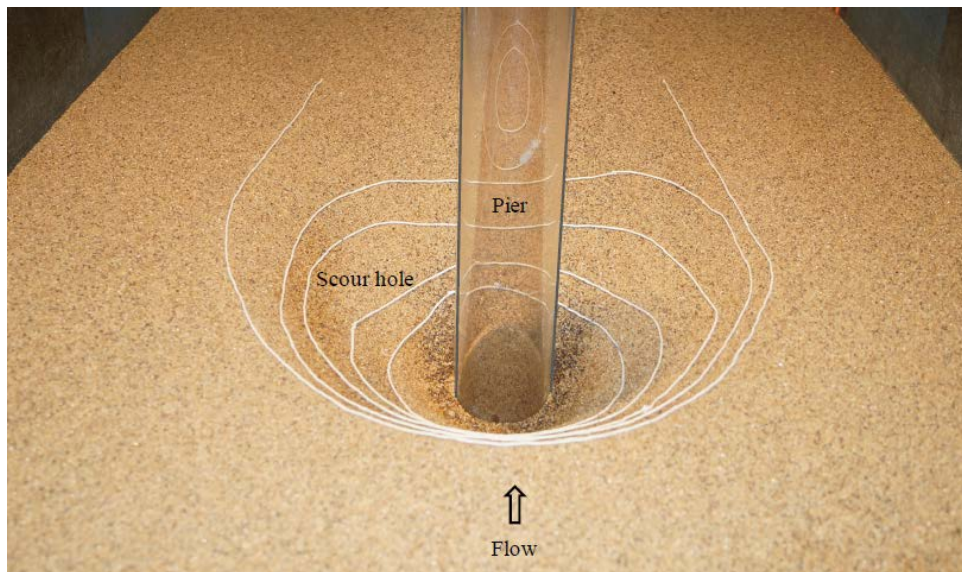


Fig. 1.2 Photograph of an equilibrium scour at a circular pier in an experimental flume

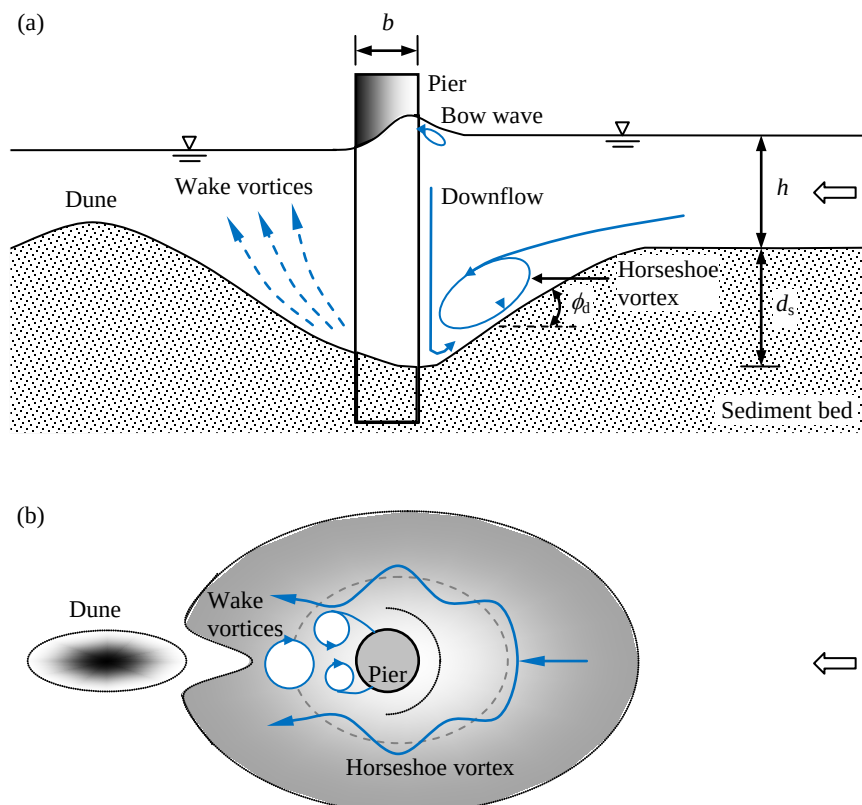


Fig. 1.3 Typical geometry of a scour hole and the components of flow field at a circular pier: (a) Elevation view and (b) plan view

The approaching flow, which is stationary at the upstream face of the pier, is maximum at the free surface and decreases to zero at the bed in the free flow (unobstructed by the pier) reach. The stagnation pressure at the upstream face of the pier decreases in the downward direction causing the flow to be driven down along the face of the pier, producing a *downflow*. The *horseshoe vortex* developed due to the flow separation at the upstream edge of the scour hole rolls to form a helical flow. It migrates downstream by the side of the pier for a few pier diameters before losing its existence becoming a part of the general turbulence. The horseshoe vortex also pushes the downflow inside the scour hole closer to the pier. The *bow wave*, formed at the free surface adjacent to the pier face rotating in a direction opposite to that of the horseshoe vortex. The stagnation pressure also accelerates the flow by the side of the pier, resulting in a flow separation at the side and creating a *wake* with the castoff vortices at the interfaces to the main flow. The castoff vortices travel downstream with the flow. Figs. 1.3(a and b) show the typical geometry of a scour hole and the components of the flow field at a pier.

1.2 Estimation of Scour Depth at Piers in Non-Cohesive Sediment Beds

Scour at piers is influenced by various parameters, which are grouped as follows:

- (1) *Parameters related to the pier*: Size, shape and orientation with respect to the approaching flow direction.
- (2) *Parameters related to the bed sediment*: Median particle size, particle size distribution and cohesiveness.
- (3) *Parameters related to the approaching flow condition*: Approaching flow velocity, approaching flow depth, shear velocity and roughness.
- (4) *Parameters related to the fluid*: Mass density, viscosity and gravitational acceleration.

A large number of empirical formulas were proposed by various investigators to estimate the maximum scour depth at piers based on the data from the laboratory experiments and the field measurements. However, a review on various formulas showed that the design formula proposed by Melville and Coleman (2000) based on available data is found to be adequately reasonable.

Melville and Coleman (2000) recommended a design formula for the estimation of maximum scour depth at piers based on empirical factors, called *K-factors*, which account for the effects of pier, flow and sediment characteristics. The *K-factors* were determined by fitting the curves that overlap the experimental and field data plots. Thus, the proposed *K-factors* potentially remain adequate from the viewpoint of a safe pier foundation design. The maximum scour depth d_s at a bridge pier formulated as a product of various *K-factors* is

$$d_s = K_h K_I K_d K_s K_\alpha \quad (1.1)$$

where K_h is the flow depth-pier size factor, K_I is the flow intensity factor, K_d is the sediment size factor, K_s is the pier shape factor and K_α is the pier alignment factor. The relationships for the *K-factors* are as follows:

The *flow depth-pier size factor* K_h is the scour depth d_s at a pier of width b for a given value of flow depth h . It is given by

$$\left. \begin{aligned} K_h(b/h < 0.7) &= 2.4b \\ K_h(0.7 \leq b/h < 5) &= 2(hb)^{0.5} \\ K_h(b/h \geq 5) &= 4.5h \end{aligned} \right\} \quad (1.2)$$

The *flow intensity factor* K_I is the ratio of the scour depth d_s for a given flow velocity U to that for the threshold flow velocity U_{cr} for the bed sediment motion. Thus, the flow intensity factor K_I represents the effects of flow intensity on scour depth. It also accounts for the nonuniformity of sediment in terms of average approaching velocity U_a at armor-peak. It is given by

$$\left. \begin{aligned} K_I &= \frac{U - (U_a - U_{cr})}{U_{cr}}, \quad \text{for } \frac{U - (U_a - U_{cr})}{U_{cr}} < 1 \\ K_I &= 1, \quad \text{for } \frac{U - (U_a - U_{cr})}{U_{cr}} \geq 1 \end{aligned} \right\} \quad (1.3)$$

where $U_a = 0.8U_{cra}$ and U_{cra} is the maximum average velocity for the bed to armor. Note that for uniform sediment, $U_a(\sigma_g < 1.4) = U_{cr}$, where σ_g is the geometric standard deviation of particle size distribution, given by $(d_{84.1}/d_{15.9})^{0.5}$ and U_{cr} is the threshold average velocity for bed sediment size d_{50} . The sampling of sediment is usually made from 2 to 4 m below the bed level.

Under varied stream flow velocities over a bed of nonuniform sediment, a process of armoring prevails resulting in an exposure of coarser particles due to washing out of the finer fractions. The armoring effect is to reduce the scour depth. The U_{cr} and U_{cra} can be obtained from

$$\frac{U_{cr}}{u_{*c}} = 5.75 \log \left(5.53 \frac{h}{d_{50}} \right), \quad \frac{U_{cra}}{u_{*ca}} = 5.75 \log \left(5.53 \frac{h}{d_{50a}} \right) \quad (1.4)$$

where u_{*ca} is the threshold shear velocity for median size d_{50a} of armor-particles, $d_{50a} = d_{max}/1.8$ and d_{max} is the maximum size of bed sediment. Melville and Coleman suggested that the u_{*c} can be empirically calculated as $u_{*c}(0.1 \text{ mm} \leq d_{50} < 1 \text{ mm}) = 0.0115 + 0.0125 d_{50}^{1.4}$ and $u_{*c}(1 \text{ mm} \leq d_{50} < 100 \text{ mm}) = 0.0305 d_{50}^{0.5} - 6.5 \times 10^{-3} d_{50}^{-1}$. Here, u_{*c} is in m s^{-1} and d_{50} in mm. For u_{*ca} , same expressions can be used replacing u_{*c} by u_{*ca} and d_{50} by d_{50a} .

The *sediment size factor* K_d is the ratio of the scour depth d_s for a given value of b/d_{50} to that for b/d_{50} for which d_s becomes maximum and beyond which there is no effect of b/d_{50} on d_s . For nonuniform sediment, d_{50} is to be replaced by d_{50a} . The K_d for sand beds is

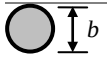
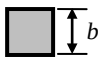
$$\left. \begin{aligned} K_d(b/d_{50} \leq 25) &= 0.57 \log \left(2.24 \frac{b}{d_{50}} \right) \\ K_d(b/d_{50} > 25) &= 1 \end{aligned} \right\} \quad (1.5)$$

However, for the piers embedded in gravel-beds, Raikar and Dey (2005b) proposed an additional set of sediment size factor. It is

$$\left. \begin{aligned} K_d(b/d_{50} \leq 9) &= 0.6 \log \left(3.88 \frac{b}{d_{50}} \right) \\ K_d(9 < b/d_{50} \leq 25) &= 0.184 \log \left(14070 \frac{b}{d_{50}} \right) \\ K_d(b/d_{50} > 25) &= 1 \end{aligned} \right\} \quad (1.6)$$

The *shape factor* K_s is defined as the ratio of the scour depth d_s for a particular pier shape to that for the circular pier having a diameter same as the pier width. The shape factors K_s for different piers are furnished in Table 1.1.

Table 1.1 Shape factors K_s for pier scour

Shape	Name	K_s
	Circular	1
	Round nosed	1
	Square nosed	1.1
	Sharp nosed	0.9

The *alignment factor* K_α is the ratio of the scour depth d_s at an oblique pier to that at an aligned pier. In case of non-circular piers, the scour depth increases with an increase in the effective projected width of the piers. The K_α is given by

$$K_\alpha = \left(\frac{b_p}{b} \right)^{0.65} \quad (1.7)$$

where b_p is the projected width of a rectangular pier normal to the approaching flow ($= L \sin \alpha + b \cos \alpha$), α is the pier orientation with respect to the approaching flow or skewness and L is the pier length (Fig. 1.4). For circular piers, $K_\alpha = 1$.

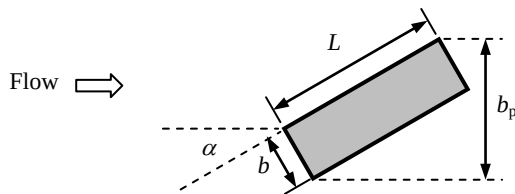


Fig. 1.4 Oblique alignment of a rectangular pier with respect to approaching flow direction

1.3 Maximum Scour Depth at Piers in Armored Beds

Riverbeds are usually composed of a mixture of different sizes of sands and gravels, especially in the upper reaches. Due to unsteady flow conditions of the stream, the coarser particles of the riverbed are exposed as a result of washing out of fines. This causes the formation of an armor-layer, which covers the finer particles and inhibits their further transport. Froehlich (1995) reported the natural armor-layer thickness being one to three times the armoring particle sizes. The armor-layers of concern to estimate scour depth at bridge piers are those where the pier is embedded in a sand-bed overlain by a layer of gravels, formed owing to the sorting of riverbed sediments (Fig. 1.5). The armor-layer extends the magnitude of threshold flow velocity for the motion of bed particles, sustaining an extended clear-water scour condition up to the limiting stability of surface particles. As a consequence of the surface particles at threshold condition, a considerably larger scour depth develops in the vicinity of a pier embedded in an armored bed (unless a secondary armor-layer developed

within the scour hole is compact enough to prevent further scouring) than if the pier were embedded in a bed of uniform sediments.

Dey and Raikar (2007) reported a formula to predict the maximum scour depth at piers in armored beds. It is

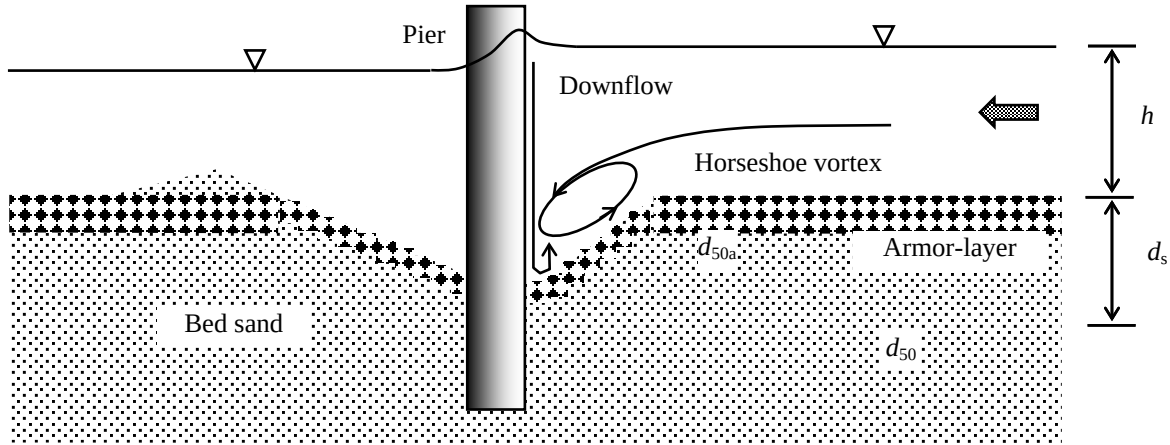


Fig. 1.5 Schematic diagram of scour at a pier in an armored bed

$$d_s = 0.16bK_s \left(\frac{U_{cra}}{\sqrt{\Delta gb}} \right)^{0.78} \left(\frac{b}{d_{50a}} \right)^{1.07} \left(\frac{h}{b} \right)^{0.6} \left(\frac{d_{50}}{d_{50a}} \right)^{0.95} \quad (1.8)$$

where Δ is $s - 1$, s is the relative density of armor gravels, g is the gravitational acceleration, d_{50a} is the median size of armor gravels, d_{50} is the median size of bed sediment and U_{cra} is the maximum average velocity for the bed to armor.

1.4 Maximum Scour Depth at Abutments in Non-Cohesive Sediment Beds



Fig. 1.6 Photograph of a wing wall abutment

Abutments, located at either end of a bridge span, are the substructures over which the bridge superstructure rests (Fig. 1.6). Akin to bridge piers, they also help to transmit the weight of the bridge including traffic to the foundation bed. Piers are located within the bridge span (Section 1.2). Scour at bridge abutments is also equally or even more responsible for failure of bridges as compared with scour at piers. Similar to bridge piers, the flow separates at the upstream of the abutment as it travels by the side of the abutment, creating a vortex trail to move downstream. The result is that the sediment bed in the vicinity of the abutment is scoured, exposing the abutment foundation that may lead to the failure of the bridge.

According to Melville and Coleman (2000), the maximum equilibrium scour depth d_s at an abutment is given by

$$d_s = K_h K_l K_d K_s K_\alpha K_G \quad (1.9)$$

where K_G is the channel geometry factor and other K -factors are designated similar to that in Eq. (1.1). The relationships for K -factors, in case of abutment scour, are given as follows:

The *flow depth-abutment size factor* K_h for abutment scour is

$$\left. \begin{aligned} K_h (l/h \leq 1) &= 2l \\ K_h (1 < l/h < 25) &= 2(hl)^{0.5} \\ K_h (l/h \geq 25) &= 10h \end{aligned} \right\} \quad (1.10)$$

where l is the abutment length (across the flow). The above K_h -factor is distinguished into short and long abutments. For short abutments ($l/h \leq 1$), the scour depth d_s is independent of flow depth h and dependent on abutment length l . For long abutments ($l/h \geq 25$), the d_s is dependent on h and independent of l . For $1 < l/h < 25$, the d_s is dependent on both l and h . Note that l is projected length for a skewed abutment.

The *flow intensity factor* K_l given by Eq. (1.3) for the case of pier scour is also applicable for the abutment scour.

The *sediment size factor* K_d for abutment scour in sand-beds is

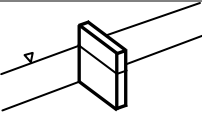
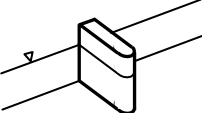
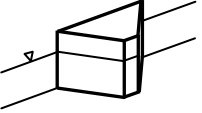
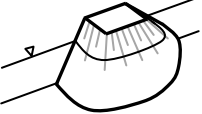
$$\left. \begin{aligned} K_d (l/d_{50} \leq 25) &= 0.57 \log \left(2.24 \frac{l}{d_{50}} \right) \\ K_d (l/d_{50} > 25) &= 1 \end{aligned} \right\} \quad (1.11)$$

However, for the abutments embedded in gravel-beds, Raikar and Dey (2005a) proposed new sediment size factors as

$$\left. \begin{aligned} K_d (l/d_{50} \leq 10) &= 1.184 \log \left(0.588 \frac{l}{d_{50}} \right) \\ K_d (10 < l/d_{50} \leq 25) &= 0.226 \log \left(1052.8 \frac{l}{d_{50}} \right) \\ K_d (l/d_{50} > 25) &= 1 \end{aligned} \right\} \quad (1.12)$$

The *shape factor* K_s is defined as the ratio of the scour depth d_s for a given abutment shape to that for the vertical-wall abutment having a same length. The shape factors K_s for different abutments are given in Table 1.2.

Table 1.2 Shape factors K_s for abutment scour

Shape	Name	K_s
	Vertical-wall	1
	Semicircular ended	0.75
	45° wing-wall	0.75
	Spill-through (Horizontal : Vertical)	
	0.5 : 1	0.6
	1 : 1	0.5
	1.5 : 1	0.45

For abutments, the values of *alignment factor* K_α for abutment scour are

$$\left. \begin{aligned} K_\alpha (l/h \geq 3) &= K_\alpha^* \\ K_\alpha (1 < l/h < 3) &= K_\alpha^* + (1 - K_\alpha^*) \left(1.5 - 0.5 \frac{b}{h} \right) \\ K_\alpha (l/h \leq 1) &= 1 \end{aligned} \right\} \quad (1.13)$$

The values of K_α^* in the above equation are obtained from Table 1.3.

Table 1.3 Factors K_α^* for abutment scour

α (degree)	30	45	60	90	120	135	150
K_α^*	0.9	0.95	0.98	1	1.05	1.07	1.08

The *channel geometry factor* K_G is defined as the ratio of the scour depth d_s at an abutment to that at the same abutment in the equivalent rectangular channel. In case of rectangular channels, $K_G = 1$. However, for abutments in compound channels, K_G depends on the abutment position in the compound channel. The K_G is

$$K_G = \left\{ 1 - \left(\frac{l^*}{l} \right) \left[1 - \left(\frac{h^*}{h} \right)^{5/3} \left(\frac{n}{n^*} \right) \right] \right\}^{0.5} \quad (1.14)$$

where l^* is the abutment length spanning the flood channel, h^* is the flow depth in the flood channel and n and n^* are the Manning roughness coefficients in the main and flood channels

($= 0.149 d_{50}^{1/6} / g^{0.5}$), respectively. In case of an inclined abutment, l and l^* are the projected abutment length and that spanning the flood channel, respectively.

1.5 Maximum Scour Depth at Piers or Abutments in Cohesive Sediment Beds

From the design consideration, scour depth at piers or abutments in cohesive sediment beds (clay beds) is less than that in non-cohesive beds. So, Melville and Coleman formula, given by Eq. (1.1) for pier scour and Eq. (1.9) for abutment scour, can be safely used.

1.6 Maximum Scour Depth within Channel Contractions

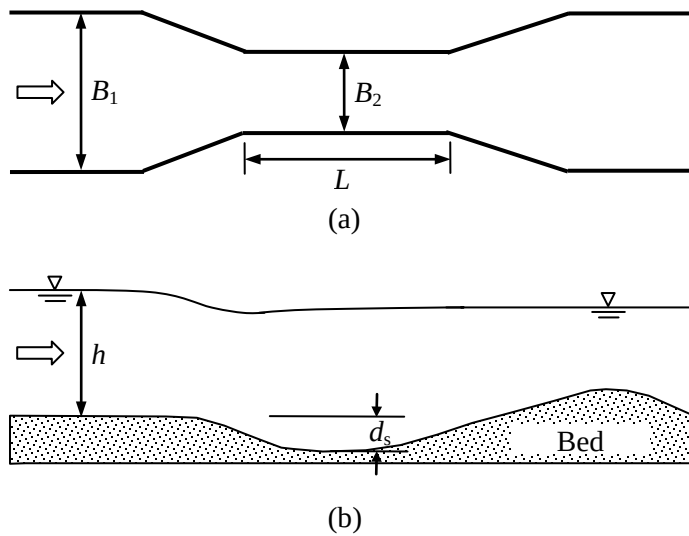


Fig. 1.7 Schematic of a rectangular channel contraction at equilibrium scour condition: (a) Plan view and (b) elevation view

A reduction of width of a watercourse by constructing parallel sidewalls is termed *channel contraction*. Contraction of a river width to construct bridges is a common example of channel contractions. The flow velocity in the contracted zone of the channel increases due to the reduction of flow area, and hence the bed shear stress induced by the flow increases considerably. Consequently, the sediment bed within the channel contraction is scoured. Such localized scour in the contracted zone of the channel is called *contraction scour*. Figs. 1.7(a and b) show schematic of scour in a channel contraction.

Lim and Cheng's (1998) formula for scour depth within channel contractions is used

$$d_s = h \left[\left(\frac{B_1}{B_2} \right)^{0.75} - 1 \right] \quad (1.15)$$

where h is the approaching flow depth and B_1 and B_2 = un-contracted and contracted channel widths, respectively.

1.7 Effects of an Upstream Pier on Scour at a Downstream Pier

The upstream pier could primarily influence the scour at a downstream pier in two ways: (1) upstream pier modifies the flow field in the wake flow region that acts as an approaching

flow for the downstream pier to scour and (2) the sediment that is scoured from the upstream pier is being fed to the scour hole at the downstream pier.

The effects of an upstream (front) pier on a downstream (rear) pier, in the context of scour, for the alignments of tandem (Fig. 1.8) and staggered (Fig. 1.9) are studied.

Piers in Tandem Arrangement

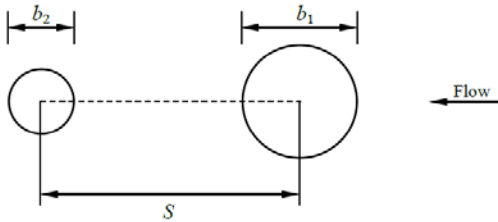


Fig. 1.8 Schematic of piers in tandem arrangement

Scour depth at front and rear pier is same and less, respectively, as the scour depth at a single pier. So, Melville and Coleman formula, given by Eq. (1.1) for pier scour, can be safely used.

Piers in Staggered Arrangement

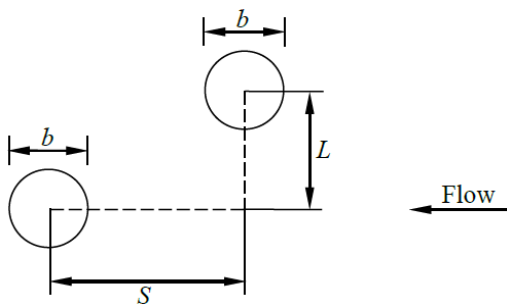


Fig. 1.9 Schematic of piers in staggered arrangement

Front pier: Scour depth at front pier is same as the scour depth at a single pier. So, Melville and Coleman formula, given by Eq. (1.1) for pier scour, can be safely used.

Rear pier: Scour depth at rear pier for $S/L \geq 2.3$ is 1.2 times the scour depth at a single pier. So, the maximum scour depth is $1.2d_s$, where d_s is calculated from Eq. (1.1). This condition should be avoided.

1.8 Equivalent Width of Non-Uniform Pier

The four cases of local scour at nonuniform piers, where the pier is founded on a wider element (caissons, slab footings and pile caps), are shown in Fig. 1.10.

- Case I, where the top of the footing, cap or caisson remains buried below the base of scour hole,
- Case II, where the top of the footing, cap or caisson is exposed within the scour hole below the general bed level,
- Case III, where the top of the footing, cap or caisson is above the general bed level, and

- Case IV, where the top of the footing, cap or caisson is at or above the water surface level.

For Case I, the local scour is estimated using the pier width b . For Case II, a procedure given by Melville and Raudkivi (1996) to estimate the size of an equivalent uniform pier can be applied. The equivalent uniform pier induces (at least) the same scour as the nonuniform pier. The procedure is therefore conservative. Melville and Raudkivi (1996), who measured scour depths at a circular pier founded on a larger concentric, circular caisson, gave the following relation:

$$b_e = b \left(\frac{h+z}{h+b^*} \right) + b^* \left(\frac{b^*-z}{b^*+h} \right) \quad (1.16)$$

where b_e is the equivalent width of a non-uniform pier, z is the distance of the top of the caisson from the original bed level and b^* is the caisson width. The above equation is restricted to the range defined by $z \leq b^*$ and $-z \leq h$ (Fig. 1.10).

The relation for b_e can be used for Case II non-uniform piers that are geometrically similar to the caisson foundation shown in Fig. 1.10, including piers founded on slab footings and piled foundation, unless the footing or the pile cap is undermined by the scour. Eq. (1.16) also applies to Case III caisson foundations and may be used to give conservative scour estimates for Case III piled foundations. For Case IV caisson foundations, the local scour is estimated using the caisson width b^* . This approach would also give a conservative estimate of Case IV local scour at a piled foundation. An estimation of equivalent width b_e is given here.

Considering a Case III with $b = 1.5$ m, $h = 5$ m, $b^* = 4$ m and $z = 1$ m, determine equivalent width b_e .

$$b_e = b \left(\frac{h+z}{h+b^*} \right) + b^* \left(\frac{b^*-z}{b^*+h} \right) = 1.5 \left(\frac{5+1}{5+4} \right) + 4 \left(\frac{4-1}{4+5} \right) = 2.23 \text{ m}$$

Note that this value of equivalent width b_e of a non-uniform pier is used as pier width b in estimation of scour depth by Melville and Coleman's method (Section 1.2).

1.9 Design Scour Depth at a Bridge Site

Design scour depth at a bridge site is the scour depth at a pier (or abutment) plus the scour depth due to channel contraction at the bridge crossing.

Note that in most of the cases, scour depth due to channel contraction at the bridge crossing is insignificant as compared to local scour depth at piers. Thus, in such cases, the design scour depth at a bridge site equals local scour depth at a pier.

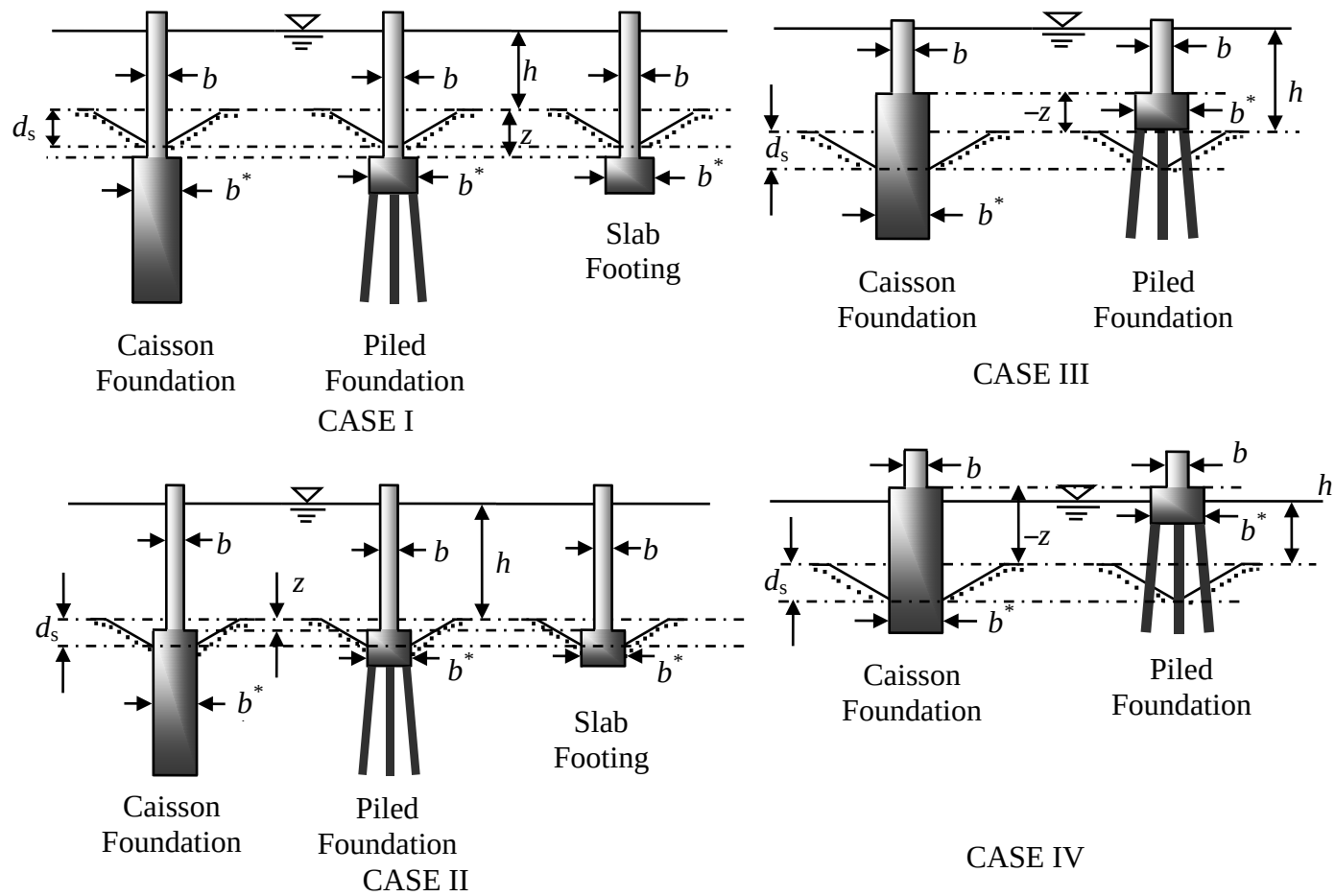


Fig. 1.10 Non-uniform pier shapes

1.10 Calculation of Scour Depth

Example 1.1 (Scour depth at a pier)

Calculate the maximum scour depth at a rectangular pier for the following data:

Pier width, $b = 2$ m

Pier length, $L = 8$ m

Approaching flow depth, $h = 8$ m

Discharge per unit width, $q = 12 \text{ m}^2 \text{ s}^{-1}$

Flow skewness, $\alpha = 15^\circ$

Median size of bed sediment, $d_{50} = 0.9$ mm (uniform sediment)

Solution

Approaching flow velocity, $U = q/h = 12/8 = 1.5 \text{ m s}^{-1}$

The threshold shear velocity and threshold approaching flow velocity are as follows:

$$u_{*c} (0.1 \text{ mm} \leq d_{50} < 1 \text{ mm}) = 0.0115 + 0.0125 d_{50}^{1.4} = 0.0115 + 0.0125 \times 0.9^{1.4} = 0.022 \text{ m s}^{-1}$$

$$U_{cr} = u_{*c} 5.75 \log \left(5.53 \frac{h}{d_{50}} \right) = 0.022 \times 5.75 \log \left(5.53 \frac{8}{0.9 \times 10^{-3}} \right) = 0.593 \text{ m s}^{-1} \Leftarrow \text{Eq. (1.4)}$$

For uniform sediment, $U_a = U_{cr}$

Computation of K -factors is as follows:

(1) For $b/h = 2/8 = 0.25 < 0.7$, $K_h = 2.4b = 2.4 \times 2 = 4.8 \text{ m} \Leftarrow \text{Eq. (1.2)}$

(2) For $\frac{U - (U_a - U_{cr})}{U_{cr}} = \frac{1.5}{0.593} = 2.53 > 1$, $K_l = 1 \Leftarrow \text{Eq. (1.3)}$

(3) For $b/d_{50} = 2/(0.9 \times 10^{-3}) = 2222.2 > 25$, $K_d = 1 \Leftarrow \text{Eq. (1.5)}$

(4) For a rectangular pier (square nosed), $K_s = 1.1$ (Table 1.1)

(5) For $b_p = L \sin \alpha + b \cos \alpha = 8 \times \sin 15^\circ + 2 \times \cos 15^\circ = 4 \text{ m}$, $K_\alpha = \left(\frac{b_p}{b} \right)^{0.65} = \left(\frac{4}{2} \right)^{0.65} = 1.569 \Leftarrow \text{Eq. (1.7)}$

Then, the scour depth is

$$d_s = K_h K_l K_d K_s K_\alpha = 4.8 \times 1 \times 1 \times 1.1 \times 1.569 = 8.284 \text{ m} \Leftarrow \text{Eq. (1.1)}$$

Example 1.2 (Scour depth at a pier plus scour depth at a channel contraction)

Calculate the maximum scour depth at a bridge site for the following data:

Pier diameter, $b = 2.5$ m

Approaching flow depth, $h = 3.4$ m

Discharge per unit width, $q = 11.9 \text{ m}^2 \text{ s}^{-1}$

Bed sediment size, $d_{50} = 20 \text{ mm}$, $d_{95} = 85 \text{ mm}$ and $d_{\max} = 99 \text{ mm}$

Consider contraction scour for the contracted width a bridge crossing as follows:

Approaching channel width, $B_1 = 70 \text{ m}$

Channel width at contracted zone, $B_2 = 50 \text{ m}$

Solution

Calculation for pier scour:

Approaching flow velocity, $U = q/h = 11.9/3.4 = 3.5 \text{ m s}^{-1}$

The threshold shear velocity u_{*c} and threshold approaching flow velocities, U_{cr} , U_{cra} and U_a , are as follows:

$$u_{*c} (1 \text{ mm} \leq d_{50} < 100 \text{ mm}) = 0.0305 d_{50}^{0.5} - 6.5 \times 10^{-3} d_{50}^{-1} = 0.0305 \times 20^{0.5} - 6.5 \times 10^{-3} \times 20^{-1} = 0.136 \text{ m s}^{-1}$$

$$d_{50a} = d_{\max}/1.8 = 99/1.8 = 55 \text{ mm}$$

$$u_{*ca} (1 \text{ mm} \leq d_{50} < 100 \text{ mm}) = 0.0305 d_{50a}^{0.5} - 6.5 \times 10^{-3} d_{50a}^{-1} = 0.0305 \times 55^{0.5} - 6.5 \times 10^{-3} \times 55^{-1} = 0.226 \text{ m s}^{-1}$$

$$U_{cr} = u_{*c} 5.75 \log \left(5.53 \frac{h}{d_{50}} \right) = 0.136 \times 5.75 \log \left(5.53 \frac{3.4}{20 \times 10^{-3}} \right) = 2.325 \text{ m s}^{-1} \Leftarrow \text{Eq. (1.4)}$$

$$U_{cra} = u_{*ca} 5.75 \log \left(5.53 \frac{h}{d_{50a}} \right) = 0.226 \times 5.75 \log \left(5.53 \frac{3.4}{55 \times 10^{-3}} \right) = 3.293 \text{ m s}^{-1} \Leftarrow \text{Eq. (1.4)}$$

$$U_a = 0.8 U_{cra} = 0.8 \times 3.293 = 2.634 \text{ m s}^{-1}$$

Computation of K -factors is as follows:

(1) For $b/h = 2.5/3.4 = 0.735$ ($0.7 \leq b/h \leq 5$), $K_h = 2(hb)^{0.5} = 2(3.4 \times 2.5)^{0.5} = 5.831 \text{ m} \Leftarrow \text{Eq. (1.2)}$

(2) For $\frac{U - (U_a - U_{cr})}{U_{cr}} = \frac{3.5 - (2.634 - 2.325)}{2.325} = 1.372 > 1$, $K_l = 1 \Leftarrow \text{Eq. (1.3)}$

(3) For $b/d_{50a} = 2/(55 \times 10^{-3}) = 36.36 > 25$, $K_d = 1 \Leftarrow \text{Eq. (1.5)}$

(4) For a circular pier, $K_s = 1$ (Table 1.1)

(5) For a circular pier, $K_\alpha = 1 \Leftarrow \text{Eq. (1.7)}$

Then, the scour depth at pier is

$$d_s = K_h K_l K_d K_s K_\alpha = 5.831 \times 1 \times 1 \times 1 \times 1 = 5.831 \text{ m} \Leftarrow \text{Eq. (1.1)}$$

Calculation for contraction scour:

The scour depth at contraction is

$$d_s = h \left[\left(\frac{B_1}{B_2} \right)^{0.75} - 1 \right] = 3.4 \left[\left(\frac{70}{50} \right)^{0.75} - 1 \right] = 0.976 \text{ m} \Leftarrow \text{Eq. (1.15)}$$

Total scour depth at bridge site is

$$d_s = 5.831 + 0.976 = 6.807 \text{ m}$$

Example 1.3 (Scour depth at a pier with an armored bed)

Calculate the maximum scour depth at a rectangular pier in an armored bed for the following data:

Pier diameter, $b = 2 \text{ m}$

Approaching flow depth, $h = 6 \text{ m}$

Bed sediment size, $d_{50} = 1.5 \text{ mm}$

Armor gravel size, $d_{50a} = 55 \text{ mm}$

Relative density of armor gravels, $s = 2.65$

Solution

Calculation for pier scour:

The threshold shear velocity u_{*ca} and threshold approaching flow velocity U_{cra} are as follows:

$$u_{*ca} (1 \text{ mm} \leq d_{50} < 100 \text{ mm}) = 0.0305 d_{50a}^{0.5} - 6.5 \times 10^{-3} d_{50a}^{-1} = 0.0305 \times 55^{0.5} - 6.5 \times 10^{-3} \times 55^{-1} = 0.226 \text{ m s}^{-1}$$

$$U_{cra} = u_{*ca} 5.75 \log \left(5.53 \frac{h}{d_{50a}} \right) = 0.226 \times 5.75 \log \left(5.53 \frac{6}{55 \times 10^{-3}} \right) = 3.613 \text{ m s}^{-1} \Leftarrow \text{Eq. (1.4)}$$

For rectangular pier, $K_s = 1.1$

$$\Delta = s - 1 = 2.65 - 1 = 1.65$$

Gravitational acceleration, $g = 9.81 \text{ m s}^{-2}$

Then, the scour depth at pier is

$$\begin{aligned} d_s &= 0.16bK_s \left(\frac{U_{cra}}{\sqrt{\Delta gb}} \right)^{0.78} \left(\frac{b}{d_{50a}} \right)^{1.07} \left(\frac{h}{b} \right)^{0.6} \left(\frac{d_{50}}{d_{50a}} \right)^{0.95} \\ &= 16 \times 2 \times 1.1 \left(\frac{3.613}{\sqrt{1.65 \times 9.81 \times 6}} \right)^{0.78} \left(\frac{2}{5.5} \right)^{1.07} \left(\frac{6}{2} \right)^{0.6} \left(\frac{1.5}{5.5} \right)^{0.95} = 3.067 \text{ m} \Leftarrow \text{Eq. (1.8)} \end{aligned}$$

Example 1.4 (Scour depth at an abutment)

Calculate the maximum scour depth at a spill-through abutment for the following data:

Abutment length = 10 m

Abutment length spanning to flood channel = 95% of abutment length

Abutment slope, $S_a = 0.5$ (horizontal) : 1 (vertical)

Abutment alignment, $\alpha = 80^\circ$

Flow depth in main channel, $h_m = 8$ m

Flow depth in flood channel, $h^* = 2$ m

Discharge per unit width in main channel, $q = 20 \text{ m}^2 \text{ s}^{-1}$

Discharge per unit width in flood channel, $q^* = 5 \text{ m}^2 \text{ s}^{-1}$

Manning coefficient in main channel, $n = 0.022$ SI units

Manning coefficient in flood channel, $n^* = 0.03$ SI units

Bed sediment size, $d_{50} = 20$ mm, $d_{95} = 85$ mm and $d_{\max} = 99$ mm

Assume the flow depth reduction to be 2% in the contracted portion.

Solution

Calculation is based on the flow in the flood channel, where 95% of abutment length exists.

Approaching flow velocity in flood channel, $U = q^*/h^* = 5/2 = 2.5 \text{ m s}^{-1}$

Projected abutment length, $l = 10 \sin \alpha = 10 \sin 80^\circ = 9.848$ m

Projected abutment length in flood channel, $l^* = 10 \times 0.95 \sin \alpha = 10 \times 0.95 \sin 80^\circ = 9.356$ m

The threshold approaching flow velocities, U_{cr} , U_{cra} and U_a , are as follows:

$u_{*c} = 0.136 \text{ m s}^{-1}$; $u_{*ca} = 0.226 \text{ m s}^{-1}$; $d_{50a} = 55$ mm (see *Example 1.2*)

$$U_{cr} = u_{*c} 5.75 \log \left(5.53 \frac{h^*}{d_{50}} \right) = 0.136 \times 5.75 \log \left(5.53 \frac{2}{20 \times 10^{-3}} \right) = 2.145 \text{ m s}^{-1} \Leftarrow \text{Eq. (1.4)}$$

$$U_{cra} = u_{*ca} 5.75 \log \left(5.53 \frac{h^*}{d_{50a}} \right) = 0.226 \times 5.75 \log \left(5.53 \frac{2}{55 \times 10^{-3}} \right) = 2.993 \text{ m s}^{-1} \Leftarrow \text{Eq. (1.4)}$$

$$U_a = 0.8 U_{cra} = 0.8 \times 2.993 = 2.394 \text{ m s}^{-1}$$

Calculation of scour depth by Melville and Coleman's method:

Computation of K -factors is as follows:

(1) For $l/h^* = 9.848/2 = 4.924$ ($1 \leq l/h^* \leq 25$), $K_h = 2(h^*l)^{0.5} = 2(2 \times 9.848)^{0.5} = 8.876 \text{ m} \Leftarrow \text{Eq. (1.10)}$

Note: As the flow depth in flood channel is applicable, h is replaced by h^* in Eq. (1.10)

(2) For $\frac{U - (U_a - U_{cr})}{U_{cr}} = \frac{2.5 - (2.394 - 2.145)}{2.145} = 1.049 > 1$, $K_l = 1 \Leftarrow \text{Eq. (1.3)}$

(3) For $l/d_{50a} = 9.848/(55 \times 10^{-3}) = 179.05 > 25$, $K_d = 1 \Leftarrow \text{Eq. (1.11)}$

(4) For a spill-through abutment with slope $S_a = 0.5$: 1, $K_s = 0.6$ (Table 1.2)

(5) For $\alpha = 80^\circ$, $K_\alpha^* = 0.993$ is obtained from Table 3. Then, for $l/h^* = 4.924 > 3$, $K_\alpha = 0.993 \Leftarrow \text{Eq. (1.13)}$

(6) K_G is calculated, considering $h = h_m$, that is the flow depth in main channel, as

$$K_G = \left\{ 1 - \left(\frac{l^*}{l} \right) \left[1 - \left(\frac{h^*}{h} \right)^{5/3} \left(\frac{n}{n^*} \right) \right] \right\}^{0.5} = \left\{ 1 - \left(\frac{9.356}{9.848} \right) \left[1 - \left(\frac{2}{8} \right)^{5/3} \left(\frac{0.022}{0.03} \right) \right] \right\}^{0.5} = 0.345 \Leftarrow \text{Eq. (1.14)}$$

Then, the scour depth is

$$d_s = K_h K_l K_d K_s K_\alpha K_G = 8.876 \times 1 \times 1 \times 0.6 \times 0.993 \times 0.345 = 1.824 \text{ m} \Leftarrow \text{Eq. (1.9)}$$

References

- Dey S, Raikar RV (2007) Clear-water scour at piers in sand-beds with an armor-layer of gravels. *Journal of Hydraulic Engineering* 133(6): 703–711
- Froehlich DC (1995) Armor-limited clear-water contraction scour at bridges. *Journal of Hydraulic Engineering* 121(6): 490–493
- Lim S-Y, Cheng N-S (1998) Scouring in long contractions. *Journal of Irrigation and Drainage Engineering* 124(5): 258–261
- Melville BW, Coleman SE (2000) Bridge scour. Water Resources Publications, Fort Collins, Colorado, United States of America
- Melville BW, Raudkivi RJ (1996) Effects of foundation geometry on bridge pier scour. *Journal of Hydraulic Engineering* 122(4): 203–209
- Raikar RV, Dey S (2005a) Scour of gravel beds at bridge piers and abutments. *Water Management, Proceedings of the Institution of Civil Engineers (London)* 158(June): 157–162
- Raikar RV, Dey S (2005b) Clear-water scour at bridge piers in fine and medium gravel beds. *Canadian Journal of Civil Engineering* 32(4): 775–781

2

Scour Countermeasures at Piers

2.1 Riprap

Ripraps most commonly used for pier scour countermeasure consist of large stones placed around a pier to armor the sediment bed (Fig. 2.1). Armoring prevents entraining bed sediment forming a scour hole due to the strong vortex flow in front of the pier. The ability of the riprap layer to provide scour countermeasure is a function of stone size, which is a critical factor in terms of shear failure. Riprap consists of a layer of stones, dumped or hand-placed on sediment bed and pier boundaries to limit the effects of erosion. It is the most common type of countermeasure due to its general availability, ease to install and relatively low cost, although it requires annual maintenance. Any successful riprap design must account for several possible modes of failure. These include riprap stone dislodgment, substrate sediment erosion and mass failure. Riprap stone dislodgment is primarily limited by sizing of the riprap to withstand hydraulic and turbulence induced forces. Substrate sediment erosion occurs when the base sediment erodes and migrates through the riprap voids causing the riprap to settle. This erosion can be limited by placing a granular filter between the riprap and the base sediment. Mass failure occurs when large sections of the riprap and/or base sediment slides or slumps due to the gravity forces. Mass failure can be caused by the excess pore water pressures; bank steepness and loss of basal support through scour. Also, a filter fabric that is too fine can block and cause the buildup of pore water pressures in the underlying soil.

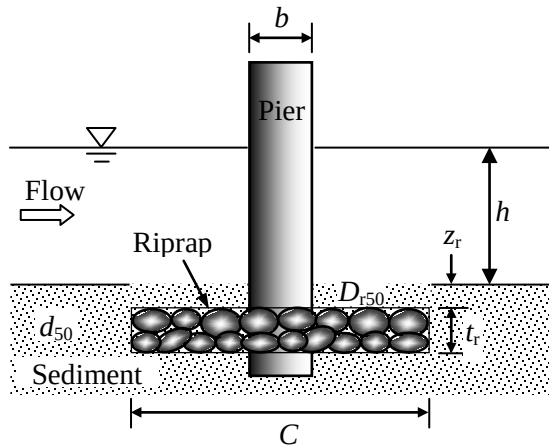


Fig. 2.1 Typical placement of a riprap layer at a pier

Riprap that is large enough to resist the hydraulic forces can fail if the scour undermines the toe support. If the riprap toe is undermined, it can shift and remain functional to some degree. Often an extra volume of riprap is included at the toe for this purpose, or the riprap toe is trenched to the depth of potential scour depth.

Lauchlan (1999) formula is recommended for determining riprap stone size D_{r50} . It is

$$D_{r50} = h \left[0.3S_f \left(1 - \frac{z_r}{h} \right)^{2.75} F^{1.2} \right] \text{ in m} \quad (2.1)$$

where h = flow depth (m), $S_f = 1.1$ as a minimum value, z_r = placement depth (m), $F = U/(gh)^{0.5}$, $g = 9.81 \text{ m s}^{-2}$ and U = flow velocity (m s^{-1})

The dimension and placement of riprap are as follows:

- The coverage length C is 4 times the pier width b
- The layer thickness t_r is 3 times the riprap stone size D_{r50}
- The placement depth z_r is one-half the pier width

2.2 Collar

A collar is made up of a horizontal plate attached to a pier (Fig. 2.2). Collar prevents the direct impact of downflow and is to reduce the scour depth by decreasing the strength of the downflow and the horseshoe vortex below the collar.

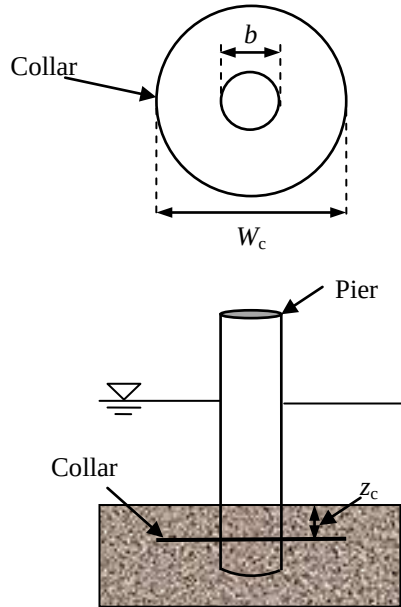


Fig. 2.2 Collar attached to a pier

It was observed that the collar width of $3.25b$, installed at $0.2b$ below the bed, produces a maximum reduction of scour depth in the range of 81–84%.

The dimension and placement of a collar are as follows:

- Use collar of width of 3.25 times pier width, that is $W_c = 3.25b$
- Use placement depth at 0.2 times pier width below the bed level, that is $z_c = 0.2b$

2.3 Threaded Pier

Cables are wrapped spirally around a pier to form the threads which can decrease the strength of the downflow and the horseshoe vortex and hence helps to reduce the scour depth. Fig. 2.3 shows single, double and triple threaded piers.

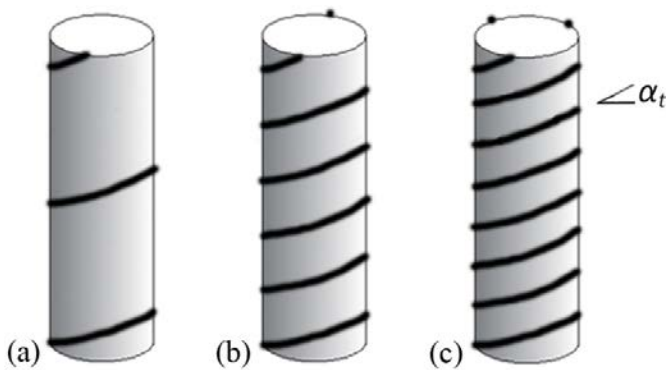


Fig. 2.3 Schematic view of threaded piers: (a) Single, (b) double and (c) triple threaded piers

It was observed that a cable–pier diameter ratio of 1 : 7.7 or 0.13 with triple threaded pier and thread angle of 15° produces a maximum reduction of scour depth as 46.58%.

The arrangement of thread is as follows:

- Use cable–pier diameter ratio as 0.13
- Use triple threaded pier
- Use thread angle as $\alpha_t = 15^\circ$

2.4 Calculation of Riprap Protection

Example 2.1

Design the riprap protection at a pier for the following field data:

Pier width, $b = 1.8$ m

Flow depth, $h = 5$ m

Flow velocity, $U = 2.1$ m s⁻¹

Bed sediment size, $d_{50} = 1.72$ mm

Solution

$$\text{Froude number, } F = \frac{U}{\sqrt{gh}} = \frac{2.1}{\sqrt{9.81 \times 5}} = 0.299$$

$$\text{Placement depth, } z_r = 0.5b = 0.5 \times 1.8 = 0.9 \text{ m}$$

$$\text{Riprap stone size, } D_{r50} = h \left[0.3S_f \left(1 - \frac{z_r}{h} \right)^{2.75} F^{1.2} \right] = 5 \left[0.3 \times 1.1 \left(1 - \frac{0.9}{5} \right)^{2.75} 0.299^{1.2} \right] = 0.225$$

m $\Leftarrow$ Eq. (2.1)

$$D_{r50} = 0.225 \text{ m}$$

$$\text{Riprap length, } C = 4b = 4 \times 1.8 = 7.2 \text{ m}$$

$$\text{Riprap layer thickness, } t_r = 3D_{r50} = 3 \times 0.225 = 0.675 \text{ m}$$

Reference

Lauchlan CS (1999) Countermeasures for pier scour. PhD thesis, The University of Auckland, Auckland, New Zealand.

3

Scour Monitoring at Piers

3.1 AquaPro Scour Monitoring Device

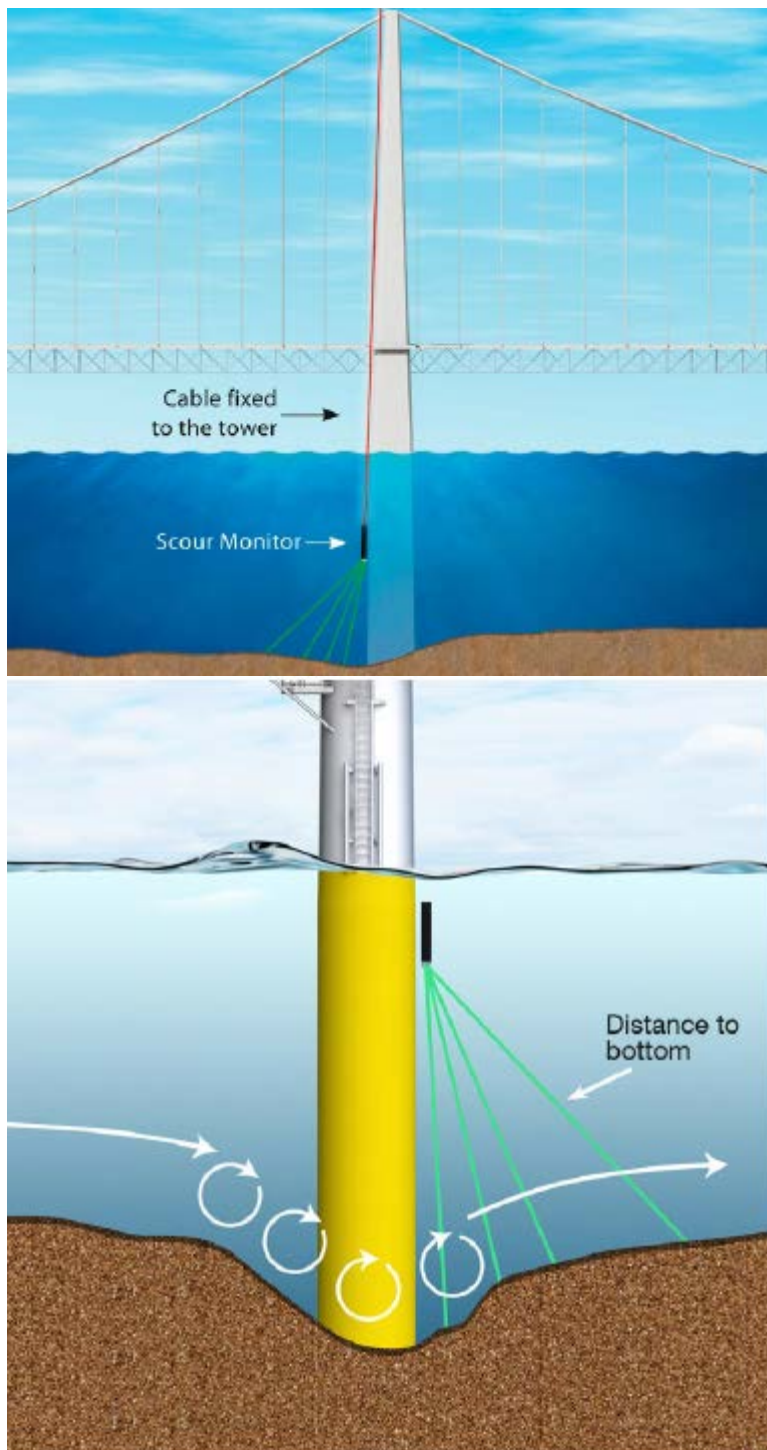


Fig. 3.1 AquaPro (Nortek manufactured) scour monitoring device installed to the bridge piers

Changes in riverbed level (scour) are measured in real-time and relayed back from the field, even during flood periods, thus providing invaluable information of these crucial changes, as they occur. Bridge foundations can easily be undermined by scour, critically affecting the stability and integrity of the structure. An online Nortek Scour monitoring device, *AquaPro*, can provide continuous and detailed information about the condition at a pier footing,

allowing the appropriate actions to be taken in during flood conditions. It also allows bridge owners to make long term planning for the maintenance purposes.

The scour monitor operates as a four beam echo sounder (Fig. 3.1). The intensity of the acoustic return signal along these four narrow beams, with angles 10, 20, 30, and 45 degrees from the vertical is measured, and due to that the bottom is a bed reflector the acoustic reflection from this provides a strong peak in signal amplitude, which is used to determine the exact distance along the beams. The software then corrects for tilt and beam angles, to provide true bottom elevation as a function of time. Data are displayed both graphically and numerically.

The bottom elevation data is either displayed online, on a password-protected web site, or stored inside the scour monitor for subsequent analysis. Fig. 3.2 shows an *AquaPro* (Nortek manufactured) scour monitoring unit. The instrument has no protruding parts, making mounting arrangements simple, with a low risk of conflict with other types of equipment and activities in the area.

The scour monitor is an inexpensive, yet powerful way of getting vital data about dynamic changes over time in bottom elevation around a wide range of bridge foundation structures.

The most common application is monitoring of scour hole development at bridge pier foundations. Bridge foundations are commonly associated with scour, where the scour monitor can provide valuable data about bottom changes as a function of time. Again, data can be displayed online or stored inside the scour monitor for subsequent analysis.

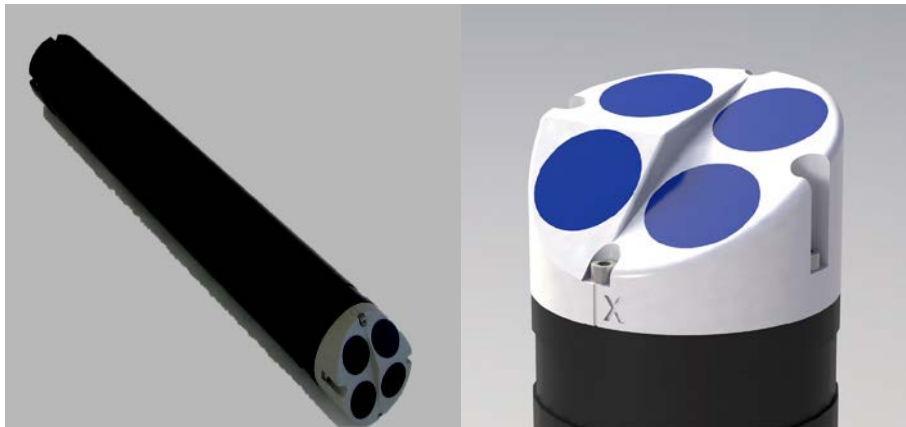


Fig. 3.2 Photograph of an *AquaPro* scour monitoring unit

3.2 Application

Preparation

- (a) Connect the battery.
- (b) Install the software located on the USB memory stick. Once the installation is done, launch the *AquaPro* scour application icon on the computer/laptop screen.
- (c) Run a functional test:
 - (i) Set the measurement interval to 1 s in the deployment planning menu. This allows to retrieve data every second.
 - (ii) Start the instrument and check if all the beams produce signals. When the instrument beeps in air, the signals are nothing but more noise.

(iii) Submerge the instrument in either a test tank or a bucket of water by holding the instrument vertical. Verify the following readings: the signal strength (it should rise prominently), battery voltage (new battery: > 13V DC), temperature and pitch and roll readings (verify these by tilting the instrument).

Configuration

(a) Select *communication* window, configure the serial port (Ex: serial port: COM2) and keep time out option to 1 s.

(b) Go to *communication* window, click on *connect* and check communication.

(c) Select *deployment planning/configuration* window.

(d) The activated dialog contains all parameters required to specify the operation of the instrument. The deployment planning frame on the right hand of the dialog displays performance parameters that are automatically updated as the settings are changed. Pay special attention to the battery utilization and the memory requirements. The maximum size of the disk memory is 9MB.

(e) When finished, press *ok* to accept the changes. By using the open/save commands in the file menu (or the corresponding toolbar buttons), the deployment parameters can be saved to file at any given time and reloaded when it is time to actually deploy the instrument.

Mode of Operation

(a) Real time mode: In this mode, data can be recorded online in real time.

(b) Deployment mode: In this mode, data can be stored after specifying the date and time.

Disk Data Recording

Select *disk data recording* menu and specify the folder name to save the data in the computer/laptop.

Start Data Recording

Start online data recording to disk.

Start Recorder Deployment

(a) Select *start recorder deployment*.

(b) Specify the date and time to start data recording.

(c) In the name field, enter text up to 6 characters to identify the data file stored in the recorder.

(d) In the file comment box, enter text up to 180 characters which will be included in the data file for the purpose of documenting the data set.

(e) After pressing *ok*, the set clock dialog box is displayed. We recommend setting the clock to PC time. The time reference is especially important in order to ensure proper synchronization between the instrument and other data sets collected independently.

(f) Press *yes* to continue. A confirmation dialog will display the deployment parameters and allow you to verify the set-up which is already defined.

(g) Press *confirm* to send the configuration to the instrument. The instrument will verify that the deployment has started. The configuration information from the deployment arrangement is saved in a log file that has the same name as the deployment.

Data Collection

(a) The fixed scour monitor instrument that takes periodic readings may be programmed for any desired interval. The streamed elevation data is normally stored in a computer/laptop and may be collected and reviewed by the designer at any desired interval. The data can be collected and reviewed under normal conditions as daily, weekly or monthly.

(b) The data collection process depends on the measurement interval (s), assumed duration (days), and memory required (MB) for the data saving. For example, if measurement interval = 1 s and assumed duration = 120 days, then memory required for data collection = 4983.4 MB.

Stop Recorder Deployment

Select *stop recorder deployment*. When data acquisition is stopped, a dialog displays the current scour monitor and PC clock time.

Data Retrieval

(a) Select recorder data retrieval.

(b) The recorder overview dialog shows a list of all files currently stored in the recorder, including the time of the first measurement and the size for each file.

(c) Select a file in the list by clicking on the filename. Press *retrieve* to specify the name and disk location of the file.

Data Conversion

(a) To convert binary data files retrieved from the recorder to a readable ASCII format, select *data conversion* from the deployment menu or press the *data conversion* toolbar button.

(b) Add files to the files to convert list by using the *add file dialog*. To convert the files, select items in the list and press the blue arrow. Specify the location for the converted files to save in a folder. An optional pre- or post-fix that will be added to the recorder filename may be specified. Select the files from dropdown lists to open the converted ASCII files in the notepad.

Online Data Collection

(a) An online data collection module is included for the test purpose and to provide data collection from the scour monitor in real time. The program will also store data to binary files on the computer hard disk for post processing and analysis.

(b) Select *start data collection* from the online menu or press the toolbar button to *start data acquisition*. The real time display shows the velocity and sensor data.

(c) To capture the data, select *disk recording* from the online menu and define the name of a file. Once the disk file is defined, the *start disk recording*, *stop disk recording* menu items and toolbar buttons will be enabled. Once the data recording has started, the status box on the display screen will show the name of the disk file and its size.

Note: Check the retrieved data before deploying the instrument for the second time measurement. If something is wrong with the instrument, deployment or configuration, this will be detected and thus the possibility of making the same mistake can be avoided.

Erase Data from Disk

Select *deployment* menu and press *erase recorder* and choose the file to erase and press *ok*.

Cable

The standard scour monitor has 8-conductors and cable with RS422 communication. The communication baud rate is 9600 for standard scour monitor and it can vary from 300 to 115200. Ensure that the connectors and dummy plugs are lubricated with dielectric silicone. We recommend 3M silicon spray. Note that the silicon grease included in the shipment should be used on the O rings only.

Power

- (a) DC input: 9–16 VDC
- (b) Battery DC input: Nominal voltage: 13.5–18 V
- (c) Absolute maximum DC input voltage: 18.6 V

Troubleshooting

As most problems are caused by simple mistakes, please initially check if

- (a) You have forgotten to power the system.
- (b) The connector has fallen out of the computer
- (c) You are using the wrong serial port.

Technical Specifications

(a) Transducer

Frequency:	1.0 MHz
Beam width:	3.4°
Beam angles:	10°, 20°, 30° and 45°
Resolution:	1–1.5 or 2–3 cm
Distance to measurement area:	1–20 m

(b) Measurement

Vertical range:	30 m
Along beam range:	45.4 m
Measurement range (vertical):	13/26 m
Accuracy:	10 or 20 cm

(c) Temperature: Thermistor embedded in sensor head

Range:	–4°C to 30°C
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Accuracy/resolution:	0.1°C/0.01°C
Time response:	10 min
(d) Tilt: Liquid level	
Accuracy/resolution:	0.2°/0.1°
Maximum tilt:	30°
(e) Data communication	
I/O:	RS422
Baud rate:	9600 standard, 300–115200 (user setting)
(f) Internal recording	
Capacity:	9 MB (expandable)
(g) Power	
DC input:	9–16 VDC (21–48 VDC w. int. DC–DC converter)
Internal battery:	18AA Alkaline cells/50 Wh
New battery voltage:	13.5 VDC
(h) Material	
Standard model:	Delrin® and polyurethane
(i) Dimensions	
Weight in air:	1.7 kg
Weight in water:	0.7 kg buoyant
Length:	590 mm
Diameter:	75 mm

4

Executive Summary of Recommendations

4.1 Estimations of Scour Depths

Local Scour Depth at Piers

The maximum scour depth d_s at a bridge pier is

$$d_s = K_h K_I K_d K_s K_\alpha$$

where K_h = flow depth-pier size factor, K_I = flow intensity factor, K_d = sediment size factor, K_s = pier shape factor and K_α = alignment factor.

The *flow depth-pier size factor* K_h is

$$\left. \begin{aligned} K_h(b/h < 0.7) &= 2.4b \\ K_h(0.7 \leq b/h < 5) &= 2(hb)^{0.5} \\ K_h(b/h \geq 5) &= 4.5h \end{aligned} \right\}$$

where h = flow depth and b = pier width

The *flow intensity factor* K_I is

$$\left. \begin{aligned} K_I &= \frac{U - (U_a - U_{cr})}{U_{cr}}, \quad \text{for } \frac{U - (U_a - U_{cr})}{U_{cr}} < 1 \\ K_I &= 1, \quad \text{for } \frac{U - (U_a - U_{cr})}{U_{cr}} \geq 1 \end{aligned} \right\}$$

where $U_a = 0.8U_{cra}$ and U_{cra} = maximum average velocity for the bed to armor. Note that for uniform sediment, $U_a(\sigma_g < 1.4) = U_{cr}$, where $\sigma_g = (d_{84.1}/d_{15.9})^{0.5}$ and U_{cr} = threshold average velocity for bed sediment size d_{50} .

The U_{cr} and U_{cra} are

$$\frac{U_{cr}}{u_{*c}} = 5.75 \log \left(5.53 \frac{h}{d_{50}} \right), \quad \frac{U_{cra}}{u_{*ca}} = 5.75 \log \left(5.53 \frac{h}{d_{50a}} \right)$$

where u_{*ca} = threshold shear velocity for median size d_{50a} of armor particles, $d_{50a} = d_{max}/1.8$ and d_{max} = maximum size of bed sediment.

$$u_{*c}(0.1 \text{ mm} \leq d_{50} < 1 \text{ mm}) = 0.0115 + 0.0125 d_{50}^{1.4}$$

$$u_{*c}(1 \text{ mm} \leq d_{50} < 100 \text{ mm}) = 0.0305 d_{50}^{0.5} - 6.5 \times 10^{-3} d_{50}^{-1}$$

where u_{*c} is in m s^{-1} and d_{50} in mm. For u_{*ca} , same expressions can be used replacing u_{*c} by u_{*ca} and d_{50} by d_{50a} .

The *sediment size factor* K_d for sand beds ($d_{50} < 2\text{mm}$) is

$$\left. \begin{aligned} K_d(b/d_{50} \leq 25) &= 0.57 \log \left(2.24 \frac{b}{d_{50}} \right) \\ K_d(b/d_{50} > 25) &= 1 \end{aligned} \right\}$$

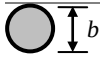
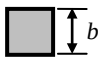
For nonuniform sediment, d_{50} is to be replaced by d_{50a} .

Sediment size factor K_d for gravel beds ($d_{50} > 2\text{mm}$) is

$$\left. \begin{aligned} K_d(b/d_{50} \leq 9) &= 0.6 \log \left(3.88 \frac{b}{d_{50}} \right) \\ K_d(9 < b/d_{50} \leq 25) &= 0.184 \log \left(14070 \frac{b}{d_{50}} \right) \\ K_d(b/d_{50} > 25) &= 1 \end{aligned} \right\}$$

The shape factors K_s for different piers are furnished in Table 4.1.

Table 4.1 Shape factors K_s for pier scour

Shape	Name	K_s
	Circular	1
	Round nosed	1
	Square nosed	1.1
	Sharp nosed	0.9

The *alignment factor* K_α is

$$K_\alpha = \left(\frac{b_p}{b} \right)^{0.65}$$

where b_p = projected width of a rectangular pier normal to the approaching flow ($= L \sin \alpha + b \cos \alpha$), α = pier orientation with respect to the approaching flow or skewness and L = pier length (Fig. 4.1). For circular piers, $K_\alpha = 1$.

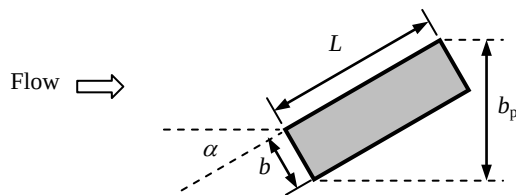


Fig. 4.1 Oblique alignment of a rectangular pier with respect to approaching flow direction

Scour Depth at Piers in Armored Beds

The scour depth at piers in armored beds is

$$d_{sa} = 0.16bK_s \left(\frac{U_{cra}}{\sqrt{\Delta gb}} \right)^{0.78} \left(\frac{b}{d_{50a}} \right)^{1.07} \left(\frac{h}{b} \right)^{0.6} \left(\frac{d_{50}}{d_{50a}} \right)^{0.95}$$

where $\Delta = s - 1$, s = relative density of armor gravels ($= 2.65$, usually), g = gravitational acceleration (9.81 m s^{-2}), d_{50a} = median size of armor gravels, d_{50} = median size of bed sediment and U_{cra} = maximum average velocity for the bed to armor.

Scour Depth at Abutments

The scour depth d_s at an abutment is

$$d_s = K_h K_l K_d K_s K_\alpha K_G$$

where K_G = channel geometry factor and other K -factors are similar to that in pier scour.

The *flow depth-abutment size factor* K_h for abutment scour is

$$\left. \begin{aligned} K_h (l / h \leq 1) &= 2l \\ K_h (1 < l / h < 25) &= 2(hl)^{0.5} \\ K_h (l / h \geq 25) &= 10h \end{aligned} \right\}$$

where l = abutment length (across the flow). The l is projected length for a skewed abutment.

The *flow intensity factor* K_l is same as that in pier scour.

The *sediment size factor* K_d for abutment scour in sand beds is

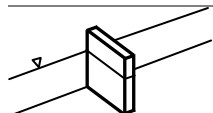
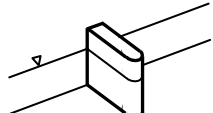
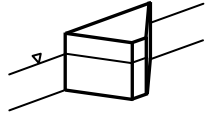
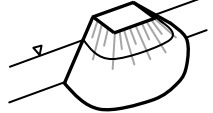
$$\left. \begin{aligned} K_d (l / d_{50} \leq 25) &= 0.57 \log \left(2.24 \frac{l}{d_{50}} \right) \\ K_d (l / d_{50} > 25) &= 1 \end{aligned} \right\}$$

The *sediment size factor* K_d for abutment scour in gravel beds is

$$\left. \begin{aligned} K_d (l / d_{50} \leq 10) &= 1.184 \log \left(0.588 \frac{l}{d_{50}} \right) \\ K_d (10 < l / d_{50} \leq 25) &= 0.226 \log \left(1052.8 \frac{l}{d_{50}} \right) \\ K_d (l / d_{50} > 25) &= 1 \end{aligned} \right\}$$

The shape factors K_s for different abutments are given in Table 4.2.

Table 4.2 Shape factors K_s for abutment scour

Shape	Name	K_s
	Vertical-wall	1
	Semicircular ended	0.75
	45° wing-wall	0.75
	Spill-through (Horizontal : Vertical) 0.5 : 1	0.6

1 : 1	0.5
1.5 : 1	0.45

The *alignment factor* K_α is

$$\left. \begin{aligned} K_\alpha (l/h \geq 3) &= K_\alpha^* \\ K_\alpha (1 < l/h < 3) &= K_\alpha^* + (1 - K_\alpha^*) \left(1.5 - 0.5 \frac{b}{h} \right) \\ K_\alpha (l/h \leq 1) &= 1 \end{aligned} \right\}$$

The values of K_α^* in the above equation are obtained from Table 4.3.

Table 4.3 Factors K_α^* for abutment scour

α (degree)	30	45	60	90	120	135	150
K_α^*	0.9	0.95	0.98	1	1.05	1.07	1.08

The *channel geometry factor* K_G is

$$K_G = \left\{ 1 - \left(\frac{l^*}{l} \right) \left[1 - \left(\frac{h^*}{h} \right)^{5/3} \left(\frac{n}{n^*} \right) \right] \right\}^{0.5}$$

where l^* = abutment length spanning the flood channel, h^* = flow depth in the flood channel and n and n^* = Manning roughness coefficients in the main and flood channels (= $0.149 d_{50}^{1/6} / g^{0.5}$), respectively. In case of inclined abutments, l and l^* = projected abutment length and that spanning the flood channel, respectively. In case of rectangular channels, $K_G = 1$.

Scour Depth at Piers or Abutments in Cohesive Sediment Beds

The scour depth at piers or abutments in cohesive sediment beds (clay beds) is less than that in non-cohesive beds. The scour depth at piers or abutments in non-cohesive sediment beds is adequate for designing pier or abutment foundation.

Scour Depth within Channel Contractions

The scour depth within channel contractions is

$$d_s = h \left[\left(\frac{B_1}{B_2} \right)^{0.75} - 1 \right]$$

where h = approaching flow depth and B_1 and B_2 = un-contracted and contracted channel widths, respectively.

Effects of an Upstream Pier on Scour at a Downstream Pier

Piers in Tandem Arrangement:

Scour depth at front or rear pier is same as the scour depth at a single pier.

Piers in Staggered Arrangement:

Front pier: Scour depth at front pier is same as the scour depth at a single pier.

Rear pier: Scour depth at rear pier is 1.2 times the scour depth at a single pier.

Design Scour Depth at a Bridge Site

Design scour depth at a bridge site is the scour depth at a pier (or abutment) plus the scour depth due to channel contraction at the bridge crossing.

4.2 Scour Countermeasures

Riprap

1. The riprap stone size D_{r50} is obtained from

$$D_{r50} = h \left[0.3S_f \left(1 - \frac{z_r}{h} \right)^{2.75} F^{1.2} \right] \text{ in m}$$

where h = flow depth (m), $S_f = 1.1$ as a minimum value, z_r = placement depth (m), $F = U/(gh)^{0.5}$, $g = 9.81 \text{ m s}^{-2}$ and U = flow velocity (m s^{-1})

2. The coverage length C is 4 times the pier width, that is $C = 4b$

3. The layer thickness t_r is 3 times the riprap stone size, that is $t_r = 3D_{r50}$

4. The placement depth z_r is one-half the pier width, that is $z_r = 0.5b$

Collar

1. Use collar of width of 3.25 times pier width, that is $W_c = 3.25b$

2. Use placement depth at 0.2 times pier width below the bed level, that is $z_c = 0.2b$

Threaded Pier

1. Use cable–pier diameter ratio as 0.13

2. Use triple threaded pier

3. Use thread angle as $\alpha_t = 15^\circ$

4.3 Scour Monitoring

AquaPro (Nortek manufactured) scour monitoring devise is recommended.

