Suitable Bridge Pier Section for a Bridge over a Natural River

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Abstract: Estimation of maximum scour depth at the bridge pier is necessary for the safety and economy of the bridge design. Therefore, the phenomenon of scour around bridge piers was extensively studied from the literature to find the effect of pier shapes and inclined flow on scour depth at bridge piers.

It was found from the analysis that scour depth increases with the increase of the flow angle relative to the pier axis, but for a cylindrical pier, maximum scour depth does not change with flow angle. When the flow angle is at 30^0, the scour depth for the cylindrical pier is smaller than other pier shapes; hence circular pier shape is more suitable for natural rivers which have possibility of changing flow direction.

Keywords: Scour Bridge pier, Pier axis, Flow angle, Cylinder

1. Introduction

Scour is the local lowering of stream bed elevation which takes place in the vicinity or round a structure constructed in flowing water. Scour take placed around bridge piers, abutments, around spur, jetties and breakwaters due to modification of flow pattern in such a way as to cause increase in local shear stress. This in turn dislodges the material on the stream bed resulting in local scour. In the case of bridges, the estimation of correct depth of scour below the stream bed is very important since that determines the depth of foundation.

Hurber [1] has stated that since 1950 over 500 bridges in USA have failed and that the majority of the failures were related to the scour of foundation material. Such data are not available for the PNG (Papua New Guinea) bridges. However, it is known to all of us that longest bridge in PNG, Markham Bridge is not fully functioning due to scour and settlement of one of its major pier.

The concern about safety of bridges is primarily due to three reasons which are: 1).inadequate knowledge about scour phenomenon when the bridges were constructed; 2). inadequate data on which the design flood was chosen and 3). increase in the loading on the bridges due to increase in size of trucks and other vehicles and their frequency of operation.

The stream bed lowering at the bridge can take place due to four primary reasons. If the bridge is located downstream of a large dam, there is a slow lowering of the bed and reduction of stream slope due to degradation. Degradation takes place when the stream transporting sediment becomes deficient in sediment supply due to sediment being stored upstream of the dam. In extreme case this lowering can be as much as 4 to 6 meters. Secondly, if for reducing the cost of the bridge the stream is contracted by building guide bunds etc…, such contraction can cause additional lowering of the stream bed.

The third type of lowering that takes place around the bridge pier is due to modification of flow structure due to presence of pier. Depending on the pier shape and free stream condition, an eddy structure comprising of one or more of the three eddy structures, namely horseshoe vortex, wave vortex and the trailing vortex system can form; which increases the local shear on the bed and causes scour. Typical formation of horseshoe vortex and wake vortex are shown in figure 1. Lastly; additional scour can also take placed if the flow direction is inclined to the pier axis.

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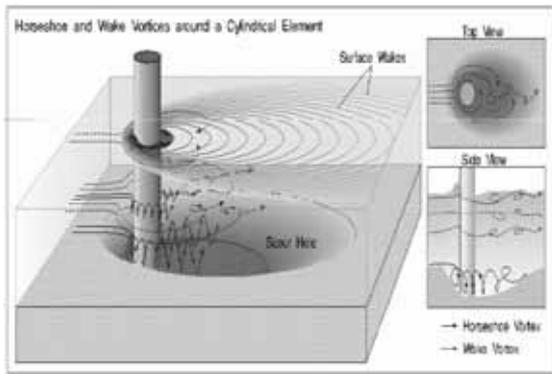
Figure 1 : Formation of Horse shoe and Wake vortexes

Eventhough, number of researchers have studied the factors affecting scouring depth and hence derived formulas to evaluate the sour depth for pier. It is not considered the combined effect of flow direction and the pier shape to select an optimum section for piers.

It can be described, when the axis of the pier makes an angle θ with the general direction of the flow, two major changes take place in the flow field. Except in the case of cylindrical pier, the separation pattern is drastically changed resulting in change in vortices. Secondly, the open width between the piers, perpendicular to the flow direction reduces as the angle of inclination θ increases.

Therefore, the combined effect of pier shapes and angle of inclination of pier axis to the flow direction on scouring depth is extremely important in pier designing. Since the depth of foundation of pier decided by the maximum scour depth, the finding of this study is more important for selecting a correct pier shape to reduce the depth of scour.

Further, most of natural river banks are not stable for long times, it may change the direction of flow due to erosion. It also possible due to deposition of sediment inside the river. Therefore it is risky to select a pier section in traditional way, just thinking that the river flow is axial. Hence, it is better to select a suitable pier section for natural river by studying the effect of flow direction.

2. Literature Review

A number of papers have been published since 1940 on various aspects of scour around bridge piers. Based on the experimental work and some theoretical analysis it is found that the following factors affect the scour depth at the bridge pier.

i) Whether the incoming flow is clear water flow or it carries sediment: clear water flow occurs when u_*/u_{*c} is less than unity while for sediment transporting flow U_*/U_{*c} is greater than unity. Here $U_* = \sqrt{gDS}$ is the shear velocity of flow and U_{*c} is the shear velocity at which bed material starts moving, D is the depth of flow in the river and S is the river slope. Average shear stress on the bed is $\tau_0 = \zeta_f U_{*se}\gamma_f DS$ where γ_f is the unit weight of water and ζ_f its mass density. All factors remaining the same clear water scour is found to be about 10 % more than scour in scour in sediment transporting flows. Further, whereas in clear water flow it takes several hours to reach the maximum scour below river bed d_{sc}, in sediment transporting flow corresponding equilibrium scour depth d_{se} is reached in relatively shorter time.

ii) Effect of change in depth of flow: experiments by Melville and Sutherland have shown that when (depth of flow/ pier width) ration i.e., D/b is greater than 2.6, scour depth does not depend on the depth of flow; for smaller depths the scour depth depends on the depth of flow.

iii) Effect of shape of pier nose: the shape of the pier nose affects the strength of horse-shoe vortex as well as the separation of the flow around the bridge pier; hence it affects the maximum scour depth. The following table 1 prepared on the basis of studies by Laursen and Toch [4], Chabert and Engeldinger [3], Garde [7], and Paintal and Garde [6], gives relative effect of pier – nose shape on the maximum scour if for cylindrical pier the maximum scour is taken as unity.

Table 1: Average values of shape coefficients (K_s)

Shape		K_s
Cylindrical		1.0
Rectangular (l/b = 2 to 6)		1.1 to 1.25
Lenticular (2:1, 3:1, 4:1)		0.93, 0.79, 0.70
Elliptical (2:1 , 3:1)		1.0 , 0.86
Joukowsky profile (4:1 , 5 :1)		1.0 , 0.80
Triangular:	15^0 apex angle	0.45
	60^0 apex angle	0.75
	90^0 apex angle	0.88
	120^0 apex angle	0.94
	150^0 apex angle	1.0

iv) Effect of angle of inclination of pier on scour depth: In this case, two major changes take place in the flow field except in the case of

cylindrical pier, the flow separation pattern is drastically changed and secondly, the open width between the piers, perpendicular to the flow direction reduces as the angle of inclination increases.

v) Effect of opening ration on scour depth: the opening ratio α is defined as $\alpha = (B-b)/B$ where B is centre to centre spacing of the piers and b is the pier width. When b is very small compared to B, α is close to unity and flow around one pier does not affect that around the other. However, as α decreases, the interference affect becomes more pronounced and scour depth increases; in such a case Dse/D or Dsc/ d- α^{-n}. Here Dse and Dsc are scour depths below the water surface for sediment transporting and clear water flows respectively. The analysis of extensive data collected by Garde [8] indicate that n = 0.30.

vi) Effect of bed material characteristics: in the case of non cohesive materials, the characteristics of bed material that affect the scour depth are sediment density, median size d of the bed material, its standard deviation and stratification. For all practical purposes the density of natural sediments can be taken as 2.65, a constant value.

As regard the sediment size, lacey-inglis approach suggests that $D_{se} \approx d^{-1/6}$. Since the average shear stress on the bed (= $\gamma_f DS$) at which bed material moves-known as the critical shear stress-increases as the sediment size increases, it stands to reason that scour depth should be affected by the size of the bed material. Hence, for given flow condition, larger than the sediment size d, smaller should be the scour depth. The clear water scour depth should decrease with increase in sediment size. Analysis of data over large of sediment size by Kothyari [9,10] has indicated that $d_{sc} \approx d^{-0.31}$ while for sediment transporting flow $d_{se} \approx d^{-0.07}$. Here d_{sc} and d_{se} are the scour depths below general bed level for sediment transporting and clear water flows respectively.

The effect of size distribution of the bed material on the scour depth is more significant. When the standard deviation σ_g of the bed material is large and the bed material contains some nonmoving sizes for a given discharge, the coarser material would tend to accumulate in the scour hole and inhibit further development of scour depth. Hence for the same median size, scour depth will be smaller for material with larger geometric standard deviation σ_g .Here

σ_g = ½ ($d_{84}/d_{50} + d_{50}/d_{16}$) and , d_{84}, d_{50} and d_{16} are such sizes that 84%, 50% and 16% material is finer than d_{84}, d_{50} and d_{16} sizes respectively.

The percentages 84 and 16 are such that for normal or Gaussian distribution d_{84}= (d_{50}+ standard deviation) and (d_{16}= d_{50} - standard deviation) if the correction factor K_σ is defined as

$$K_\sigma = \frac{\text{Equilibrium scour depth for non-uniform material}}{\text{Equilibrium scour depth for uniform material of the same median size}}$$

K_σ would depend on σ_g . On the basis of experiment data of Raudkivi [11] and Kothyari [10] the following table is given.

Table 3: Variation of K_σ with σ_g

σ_g	1.0	1.5	2.0	2.4	2.75	3.3
K_σ	1.0	0.9	0.75	0.5	0.38	0.25

Vii) Stratification: Ettema [26] have studied the effect of stratification of the bed material on scour depth in case of clear water scour. It is concluded that the stratification, in which a relatively thin coarse top layer covers a thick fine bottom layer, is the critical condition. Once the top coarse layer is scoured away, scour depth will rapidly increase.

viii) Effect of flow parameters

Based on certain theoretical analysis, physical reasoning and analysis of experimental data, investigators have arrived at the basic flow parameters to which the dimensionless scour depth is related. There are equations derived by different researchers to find the scour depth, but most of this type of relationship is valid for cylindrical piers. Also these equations are valid for nearly uniform bed material. However, there are commonly used formulae to estimate the bridge pier scour depth , some of these are; Lacey-Inglis Equation , laursen-Toch Equation, Kothyari-Garde-Ranga Raju's Method and Colorado Sate University Equation. Almost all these formulae were developed based on the laboratory data. This is because the scour is a very complex phenomenon that has resulted from the interaction between the flow around a bridge pier and the erodible bed surrounding it. Based on this, only very limited attempts have been successful in modeling the scour computationally. However, the formulae and

models derived from these attempts are usually applied by the civil engineers to evaluate the depth of local scour for new bridges and existing bridges that have local scour problems.

In the earlier part of this century Lacey-Inglis analysed the data from stable irrigation canals flowing through loose noncohesive sandy material in Indo-Gangetic plain and obtained the following equations for depth (or hydraulic radius) D_{LQ} and perimeter (or width) P.

$D_{LQ} = 0.47(Q/f)^{1/3}$ and

$P = 4.75 \sqrt{Q}$

Where Q is the discharge in m³/s, D_{LQ} and P are in m and f is Lacey- Inglis silt factor related to median size of the bed material d by the equation

$f = 1.76 \sqrt{d}$

d in mm. on the basis of analysis of scour data on 17 bridges in alluvial rivers in North India, Iinglis found that maximum scour depth below water level, D_{se} is related to computed value of D_{LQ} as $D_{se} = KD_{LQ}$, Where K is varied from 1.7 to 2.59 with an average of 2.09. Hence according to Inglis, D_{se} is given by the equation $D_{se} = 2.0\, D_{LQ}$

The equation proposed by Laursen and Toch for prediction of d_{se} is $d_{se}/D = 1.35\,(b/D)^{0.70}$ and the more commonly used and cited local scour formulae, namely the Colorado State University (QSU) is described below:

$$\frac{d_s}{y} = 2.0 K_1 K_2 \left[\frac{b}{y}\right]^{0.65} F_{r_1}^{\,0.43}$$

Where d_s is scour depth, y is flow depth at the upstream of the pier, K_1 is correction factor for pier nose shape, K_2 is correction factor for the angle of attack flow, b is the pier width and F_{r1} is the Froude number at up stream of the pier. L is the pier length. K_1 and K_2 are obtained from Table 4 and 5.

Table 4: Values of K_1 for different pier types

Type of pier	K_1
Square nose	1.1
Round nose	1.0
Circular cylinder	1.0
Shape nose	0.9
Group of cylinders	1.0

Table 5: Values of K_2 for different pier types

K_2			
Angle of flow attack	L/b = 4	L/b = 8	L/b =12
0⁰	1.0	1.0	1.0
15⁰	1.5	2.0	2.5
30⁰	2.0	2.5	3.0
45⁰	2.3	3.3	4.3
90⁰	2.5	3.9	5.0

It is recommended that the limiting value of d_s/y is 2.4 for $F_{r1} \le 0.8$ and 3.0 for $F_{r1} > 0.8$.

3. Calculation of Maximum Scour

Eventhough, few acceptable equations are available to find maximum depth of scour, In this section, the most widely used Colorado State University Equation was used. Maximum scour depths were calculated for three different flow conditions with sediment size of 1mm. The flow condition were selected by referring to the local river, namely Markham River and selected three set of data as follows:

1) Discharge 'Q' = 11200m³/s, velocity 'V' = 5.0 m/s, mean flow depth = 4.0m.

2) Discharge 'Q' = 8960 m³/s, velocity 'V' = 4.0 m/s, mean flow depth = 4.0m.

3) Discharge 'Q' = 7168 m³/s, velocity 'V' = 3.2.0 m/s, mean flow depth = 4.0m.

Further, in the first part of the calculation, four different pier shapes were considered to find the effect of pier shape on scour depth. In the second part of the calculation, effects of flow directions were considered.
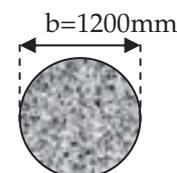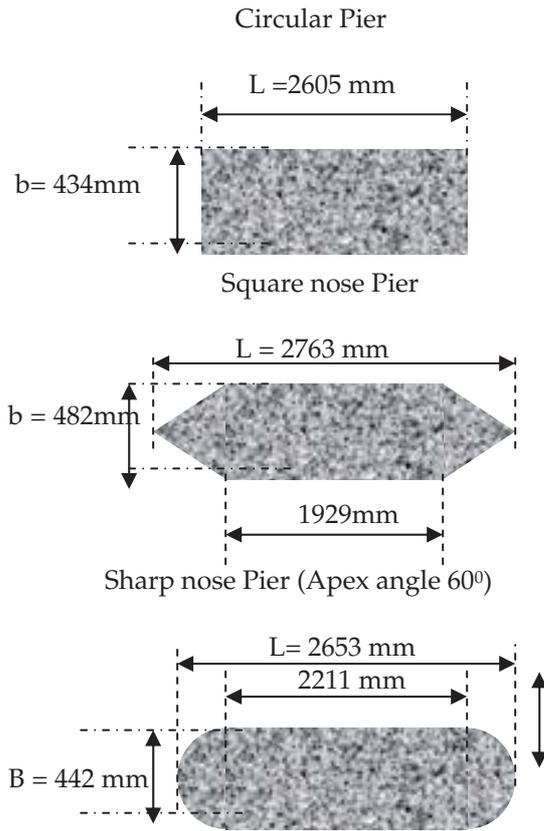
3.1 First Part of Calculation

Colorado state university equation $\frac{d_s}{y} = 2.0 K_1 K_2 \left[\frac{b}{y}\right]^{0.65} F_{r_1}^{\,0.43}$ was used to calculate the maximum scour depth for the following pier shape which are having same cross sectional areas. The results are given in table 6.

b=1200mm

Circular Pier

L =2605 mm

b= 434mm

Square nose Pier

L = 2763 mm

b = 482mm

1929mm

Sharp nose Pier (Apex angle 60⁰)

L= 2653 mm

2211 mm

B = 442 mm

Round nose Pier
Figure 2: Pier Shapes

Table 6: Maximum depth of scour for axial flow

Pier Shape	Maximum Scour Depth / m		
	Flow condition 1	Flow condition 2	Flow condition 3
Circular	3.32	3.02	2.74
Square nose	1.72	1.56	1.41
Sharpe nose	1.65	1.50	1.36
Round nose	1.74	1.58	1.43

3.2   Second Part of Calculation

Data from table 4, 5 and 6 were used to calculate the scour depth for angular flow attack and results are given in table 7 to 9.

Table 7: Maximum depth of scour variation with flow angle for flow condition 1

Flow angle (θ)	Maximum Scour Depth / m			
	Circular	Square nose	Sharp nose	Round nose
0⁰	3.32	1.72	1.65	1.74
15⁰	3.32	3.01	2.90	3.05
30⁰	3.32	3.81	3.71	3.92
45⁰	3.32	4.82	4.62	4.87

Table 8: Maximum depth of scour variation with flow angle for flow condition 2

Flow angle (θ)	Maximum Scour Depth / m			
	Circular	Square nose	Sharp nose	Round nose
0⁰	3.02	1.56	1.50	1.58
15⁰	3.02	2.73	2.63	2.77
30⁰	3.02	3.51	3.38	3.56
45⁰	3.02	4.37	4.2	4.42

Table 9: Maximum depth of scour variation with flow angle for flow condition 3

Flow angle (θ)	Maximum Scour Depth / m			
	Circular	Square nose	Sharp nose	Round nose
0⁰	2.74	1.41	1.36	1.43
15⁰	2.74	2.47	2.38	2.50
30⁰	2.74	3.17	3.06	3.22
45⁰	2.74	3.95	3.81	4.00

4.   Results and Discussion

It can be seen from the table 6 that maximum scour depth varies with the pier shape eventhough the flow and sediment conditions are equal. These results are in comparable nature since all the pier sections have equal cross sectional areas. Therefore, it can be stated that maximum scour depth occurs when the pier shape is cylindrical. Also it can be concluded that minimum scour occur when the pier shape is sharp nose. The depth of scour is decreased with flow velocity decreases, while maintaining the maximum scour and minimum scour at circular and sharp nose respectively.
On the other hand, it can be seen from the reading at table 7 to 9 that scour depth

increases with the increase of the flow angle. But, the scour depth for cylindrical pier does not change with the flow angle. This is due to the flow properties and geometrical properties of cylinder are not changed with the direction of the flow. But in other cases it will increases due to modification of flow properties and contraction of flow due to changing clear width of flow. This is represented by K_2 value at table 4 and also taken into account in the calculation. It also can be seen from the values of table 7 to 9, when the flow angle is 30^0, the calculated scour depths for square nose, round nose and sharp nose are larger than the cylindrical pier and further increases with the increase of the flow angle.

5.   Conclusion

In a natural river, it is always possible to change the flow direction due to erosion or deposition of sediments. Therefore any bridge pier constructed in a natural river could experience angular flow attack. Hence it is not recommended to evaluate maximum scour depth for a bridge pier by considering the flow as axial. It is clearer from the analysis results optimum pier section for the pier is circular section, since it has a minimum scour depth with considering all possible scenarios on scour at bridge pier. However if the engineer need to design bridge with different shapes of pier, it is necessary to consider the scour for angular flow conditions. If the pier shape is not a constrain for the design of a bridge, it is economical and safer to design the bridge with circular piers.

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