DESIGN SCOUR DEPTH FOR PIERS OF BERTHING STRUCTURE ON GANGA RIVER

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Summary

The paper describes the empirical methods and river modelling that have been used in the computation of design scour depth for the pier foundation works of the berthing structure, also known as RO-RO (Roll-on-roll-off) ramp or approach trestle. The case study of total scour depth estimation for RO-RO ramp at Sahibganj for the Jharkhand Urban Infrastructure Development Company (JUIDCO) Project - Riverfront development on Ganga River has been presented. The approaches to scour estimate take advantage of various regime theories postulated in the past researches, which are generally applied in the hydraulic design of bridges. It also investigates the other bed dynamics upstream and downstream of bridge piers during the flood; research and guidelines by Melville [1] and CIRIA [2]. For the design flood values at the aforesaid locations, the total scour depth has been estimated based on the above and recommendations have been made for the design scour depth.

Keywords: RO-RO; approach trestle; berthing structure; regime theory; general scour depth, contraction scour depth; local scour depth; total scour depth.

1. Introduction

The berthing structure or the approach trestle on a river flood plain, hereafter known as the RO-RO ramp is like a bridge structure that is usually constructed to facilitate the smooth transition of vehicle movements into the navigational vessels. The entry of vehicles to the vessel is called Roll-on, whereas the exit from the vessel is called Roll-off. Hence, the name Roll-on-roll-off (RO-RO) but it is widely observed that the entry to the vessels is not limited to vehicles; passengers and other logistics also are carried in RO-RO vessels. As these vessels are in operation on Ganga River at Sahibganj, Jharkhand, India, as a part of the riverfront development project, the RO-RO ramp project has been taken up to facilitate the permanent location of berthing of the RO-RO vessels. These vessels need sufficient drafts and under keel clearances as per the PIANC (the World Association for Waterborne Transport Infrastructure) guidelines and depending upon the variability of the water depth on the bank of the floodplain the berthing location is proposed and finalized followed by the planning and design of RO-RO ramp.

The present case study of Sahibganj RO-RO ramp features a structure taking off from the right bank of the Ganga River. The structure is similar to a declined bridge (submersible) with substructures as twin piers structures at various intervals, thereby terminating the structure at the location of berthing on the flood plain. The hydraulic design of RO-RO ramp essentially includes the scour depth estimation at the pier locations. As the structure is primarily a bridge, the convention applied for the estimation of scouring is similar to that of the bridges in flood plains. A 100-year flood has been adopted for the hydraulic design of the RO-RO ramp, thereby considering the regime depth and the width using various empirical methods for general scour depth estimation, CIRIA [2]. However, with the available surveyed cross-sections of the Ganga River at Sahibganj reach, the steady-state physically-based numerical model has been developed to assess the various flood levels, flood extents, and the fraction of discharge in the flood plains that are required for the estimation of contraction scour, Melville [1]. From the various factors, such as the depth size, shape, alignment, channel geometry, flow intensity, and the sediment size factors, the local scour depth has been estimated, Melville [1]. The accumulated depths of scour from the general, contraction, and local scour depths determine the total scour depth, which is recommended as the design scour depth for the RO-RO ramp structure.

2. Theoretical background of scour in alluvial rivers

2.1 Regime theory

The regime theories have been postulated by many hydraulicians and river engineering experts in the past for alluvial rivers. These theories indicate that knowing the silt grade and the discharge, the dimensions of a channel can be uniquely determined [3]; meaning that given the maximum discharge and the silt grade, the maximum flood scour at a bridge site and the required minimum waterway could be computed. However, in practice, it is too ideal to observe it. The empirical methods derived from such theories have been applied in some of the major rivers of the world, such as Mississippi River in USA and Sind River in Pakistan [3]. One or more of these methods have now become customary constitutions in several guidelines, such as Indian Road Congress (IRC) [4] recommending Lacey's regime equations despite the methods have many limitations.

2.1.1 General context on guidelines and standards (codes)

In general, designers are adaptive to codes because their legitimacy is unquestionable unless the standard makers review their own published documents. However, when it is a matter of guideline, the provisions within it may be challenged in the court of law, when discrepancies are widely alarmed. But when the codes and guidelines both are referring to each other with possible words, such as "may be referred to…", it results as a puzzle, which is likely to be ignored by the designer, and the "may be" is often read as "must be" and the work continues. The reason to highlight the above has been clarified at the end of the subsequent section.

2.1.2 Guidelines and standards on scour depth

To the extent that the hydraulic mean depth or the regime depth (R) for a given discharge is considered as normal scour depth by IRC [4] and Bureau of Indian Standards (BIS) [5] is purely empirical based on Lacey's theory and R is based on the L/W ratio (the ratio of the linear waterway (L) to regime width (W) of the river) conditions as follows:

$$If\ \frac{L}{W} < 1,\ R = 1.35\left(\frac{q^2}{K_{sf}}\right)^{\frac{1}{3}} \quad ...(1)$$

$$If\ \frac{L}{W} > 1,\ R = 0.47\left(\frac{q^2}{K_{sf}}\right)^{\frac{1}{3}} \quad ...(2)$$

$$K_{sf} = \text{silt factor} = 1.76\sqrt{d_{50}} \quad ...(3)$$

where, d_{50} = median particle (sediment) size.

It is to be noted that the regime depth (R) as mentioned in equations (1) and (2) is denoted by (D) in IRC: SP:13-2004 and (d_{sm}) in both IRC:78-2014 and IS 7784 (Part 1): 1993. Similarly, the discharge per unit width of the considered effective clear waterway (q) in the said equations is denoted by (Q) in IRC: SP:13-2004, (D_b) in IRC: 78-2014, and (D_i) in IS 7784 (Part 1): 1993. Therefore, to avoid the confusion over notations, the letters (R) and (q) have been unanimously used for regime depth and discharge per unit width of the considered effective clear waterway, respectively.

But it is further recommended in the aforesaid guidelines and codes to adopt the maximum scour depth as multiples of R as follows:

For bridge and aqueduct piers, maximum scour depth = 2R; and

For abutments, maximum scour depth = 1.27R.

The above factors to estimate the maximum scour depth are widely used in practice for all design works in the said context. But it is worthy to note here that neither the said guideline nor the code has substantiated the above factors that have been applied to normal scour depth, R. Designers may prefer to stick to the recommended multiples of R as the maximum scour depth. However, these recommendations leave speculations to researchers, which inevitably demands investigations to find reasonable answers. The following questions arise:

a) Based on what analysis, the maximum scour depth around piers and abutments have been concluded to be 2R and 1.27R, respectively?

b) Assuming the analysis was statistical or mathematical, the observed maximum scour depth data must have been the basis. The question is, how and when were the observations made? How many such observations were made? Were the observations justified for maximum scour depth? Who researched to find the multiples of R? If such research is in the public domain, why is it not disclosed as a reference document by either any code or guideline?

c) Question b) assumes the analysis to be purely statistical or mathematical. What about the physical processes due to obstruction other than regime conditions, such as contraction scour and local scour? Would they equate to the multiples of R as recommended above?

These are some of the vital questions that need further research in terms of justifying the multiples of R. However, the intent of the presented work is to provide a reasonable assessment of scour analysis, which is under the footprints of Melville [1] and CIRIA [2]. The various types of scour have been discussed in the subsequent section.

2.2 Types of scour

The types of scour are as follows.

1) General scour;
2) Contraction scour; and
3) Local scour

The Fig.1 displays longitudinal and cross-section sketches of various types of scour.

2.2.1 General scour

The general scour is the result of river processes causing erosion of the channel boundary and can include long-term bed degradation, aggradation, regime conditions, and lateral migration through bank erosion, bend scour and confluence scour. The regime theories are considered here to estimate the general scour among which Lacey's theory, as recommended by IRC and BIS, is one of them. It means that the R considered as normal scour depth is none other than the general scour depth. However, CIRIA [2] recommends the application of various empirical methods based on regime conditions for an average estimate of the general scour depth, R. To avoid any confusion, hereafter the "normal scour depth" shall be read as "general scour depth" and be denoted by R.

2.2.2 Contraction scour

Contraction scour is the result of confining the width of the river channel, for example between bridge

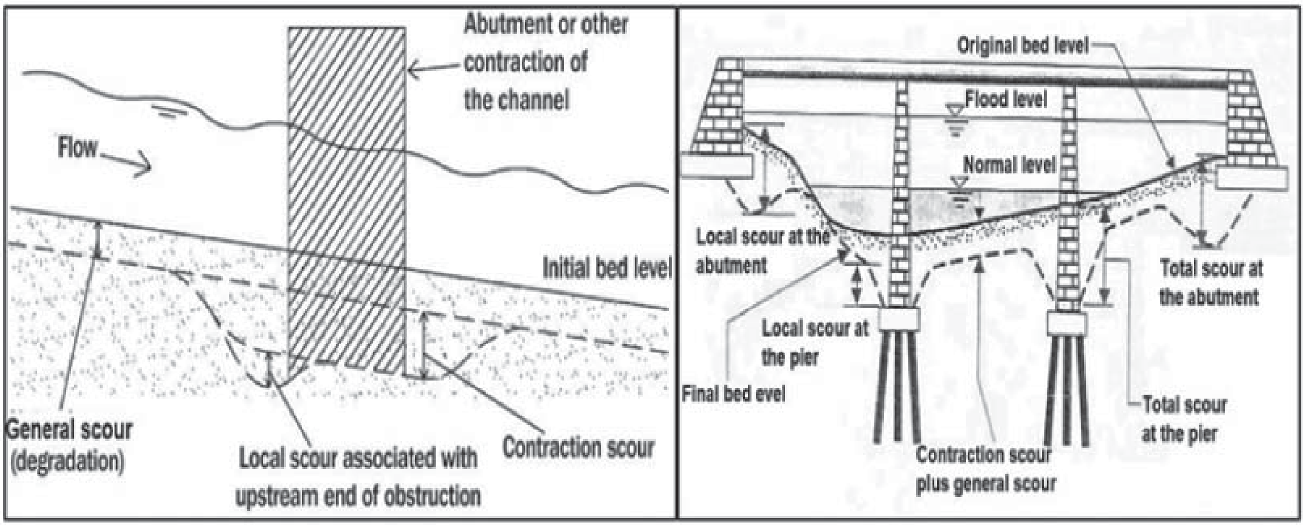

Fig.1: Types of scour (image source: [1] and [2])

abutments and piers. A major part of the contraction is often due to the approach embankments to a bridge, which cause the flows on the floodplain to join the main channel and pass through the bridge opening. The contractions affect all or most of the channel beds as displayed in Fig.1 in the vicinity of a bridge or other hydraulic structure, associated with higher velocities and shear stresses caused by the narrowing of the channel.

2.2.3 Local scour

Local scour is associated with particular local features that obstruct and deviate the flow, such as bridge piers, abutments, and dykes. The local scour occurs in the immediate locality. The structures increase the local flow velocities and turbulence levels and, depending on their shape, can lead to vortices that exert increased erosive forces on the adjacent bed. As a result, the rates of sediment movement and erosion are locally enhanced around the structures, leading to local lowering of the bed relative to the general level of the channel.

3. Case study of RO-RO ramp at Sahibganj

3.1 RO-RO ramp layout and planning

The present case study of Sahibganj RO-RO ramp features a structure similar to a declined bridge (longitudinal slope 1:11) terminating at a distance of 85,97m from the right bank towards the floodplain as displayed in Fig.2.

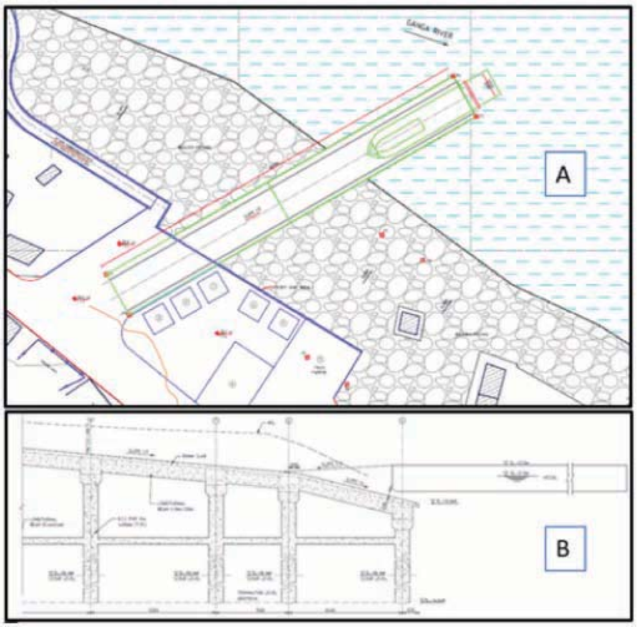

Fig.2: Schematic plan (A) and sectional view (B) of the RO-RO ramp at Sahibganj

3.1.1 Key features

The sub-structure in the RO-RO ramp constitutes twin piers of 1,40m diameters spaced c/c 7,50m apart along the axis perpendicular to the longitudinal axis of the ramp, whereas 9 set of twin piers (total number of piers = 18) are longitudinally placed mostly at regular intervals of 12,00m except at 3 locations, where the interval ranges from 5,00m to 10,90m as displayed in the image B of Fig.2. The heights of each set of twin piers vary; the highest being at the bank and lowest at the termination end.

3.2 River modelling

Although the empirical methods for regime depth are independent and do not necessarily require hydraulic modelling of the river reach, the hydraulic profile of the river for various floods are always informative for depth assessment, the flood plain fragments of discharges, etc.. The Table 1 features the surveyed cross-sections of Ganga River that have been used to model the river reach near Sahibganj with reach length equal to 20 kms.

The XS Ch.(-16500) is the representative cross-section near which the RO-RO ramp is planned.

3.2.1 Brief description of the applied software, HEC-RAS

The software, HEC-RAS developed by USACE is designed to perform one-dimensional (1D) and two-dimensional (2D) hydraulic computations numerically for a full network of natural and constructed channels. The HEC-RAS model comprises two major components; steady flow and unsteady flow. In the present study, the steady-state component has been used to calibrate the model. The physical laws which govern the flow of water in a stream or channel are expressed mathematically in the form of partial differential equations:

Conservation of mass (continuity) equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + q_1 = 0 \qquad ...(4)$$

Conservation of momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f - S_o\right) = 0 \qquad ...(5)$$

where:

Q = discharge,

A = total flow area,

Table 1: Cross-sections of the Sahibganj reach of the Ganga River (XS 0 upstream to XS -20000 downstream)

Cross-sections (XS)	Chainage, Ch. (m)	Cross-sections (XS)	Chainage, Ch. (m)
1	0	8	-15500
2	-3000	9	-16000
3	-6000	10	-16500
4	-9000	11	-17500
5	-12000	12	-19000
6	-14500	13	-19500
7	-15000	14	-20000

q_1 = lateral inflow per unit length,

x = distance along waterway,

t = time,

V = velocity,

g = acceleration due to gravity,

h = depth of flow,

S_f = frictional slope, and

S_o = bed slope.

HEC-RAS has the capacity to solve the aforesaid equations numerically and is widely used for the said cause. The computation of scour at bridges within HEC-RAS is based upon the methods outlined in Hydraulic Engineering Circular No. 18 (HEC No. 18, FHWA, 2001). However, HEC-RAS has not been updated to the Federal Highways latest procedures documented in HEC No. 18, Evaluating Scour at Bridges (FHWA, April 2012) [6].

3.1.1 Model set up and calibration

Using the surveyed cross-sections listed in Table 1 and the available data of water levels at ferry ghat of Sahibganj, a steady state model in HEC-RAS has been developed and calibrated. The Manning's roughness values (n = 0.045 for the main channel and n=0.05 for left and right overbanks) have been applied and the results concur with the previous study (Final Detailed Project Report for riverfront development at Sahibganj, Volume I: Report and Cost estimates, WAPCOS 2015).

3.3 Data organization

3.3.1 Input data

The following are the input data for the determination of regime depth. All mentioned levels are in meters above mean sea level (masl).

3.4 Empirical methods for scour depth estimate

3.4.1 Regime width (Lacey's equation)

The regime width is worked out by initially determining the wetted perimeter of the river based on Lacey's equation as tabulated in Table 3 below.

Lacey's equation for waterway equates the regime width (W) and the wetted perimeter (P) as (W = P) [4] for wide alluvial streams. However, the actual waterway to be provided under a bridge may substantially differ from Lacey's waterway depending on the terrain condition [7]. If the structure (hypothetical bridge) is a proposed one at a site where no other bridge structure existed before, the designer has the freedom to provide the waterway required [7]. The Ganga River at Sahibganj reach in the present case study is highly alluvial and is composed of braided channels. However, at the HFL the flood extent reaches the floodplain and the linear waterway, L (the span of the hypothetical bridge from abutment to abutment) = 6040m. When P << L and if the considered clear waterway, W = P, the discharge per unit width (q) is significantly higher and unjustifiable as the stability of the alluvial floodplain remains unwarranted, thereby leading to overestimation of the

Table 2: Input data

Particulars	Name or value	Unit
Name of river	Ganga	-
Location	Ferry ghat, Sahibganj	-
Catchment area (Ac)	1048409	Km^2
Design flood frequency	1 in 100	Year
Design flood (100-Year flood) (Q_d)	90096	m^3/s
Highest flood level (HFL) in the river	32,6	masl
Lowest river bed level(LRBL)	10,17	masl
River bed level at the pier end of the berthing structure (RBLp)	21,5	masl
River top width w.r.t. HFL (T)	6040	m
Cross-sectional area of river at HFL (A_d)	68181,2	m^2
Wetted perimeter of the river at HFL(P_d)	6053,54	m
Depth of water in river (y)	22,43	m
Median size bed material (d_{50})	0.15	mm

Table 3: Regime width computation

Particulars	Value	Unit
Design flood (Q_D)	90096	m^3/s
Wetted perimeter of the river, P = 4,8*(Q)^0,5 =	1440,77	m
Linear waterway as per river cross-section (L)=	6040,00	m
Considered Clear Waterway W= (1,5*P)= Regime width	2161,15	m
Velocity during design flood ($v = Q_D/A_d$)=	1,32	m/s

general scour. However, when P << L and if the considered clear waterway, W ≈ L, the discharge per unit width (q) reduces, thereby underestimating the general scour. Ideally, had the design been sought for an actual bridge at the said location, the clear waterway would have been recommended to be W ≈ L. However, considering the case of RO-RO ramp in the floodplain, the effective clear waterway shall be such that its impact on the floodplain in terms of general scour estimation is significant and acceptable. Therefore, instead of considering W =P; where P is about $1/4^{th}$ of the linear waterway L, an effective clear waterway of W = 1.5P has been considered; which is about $1/3^{rd}$ of the value of L. It preserves the design to be on the conservative side, thereby avoiding the overestimation and underestimation of general scour.

3.4.2 General scour by Lacey's waterway method

From the median size bed material (d_{50}), the silt factor is obtained and the regime depth is obtained using the equation (1) and (2).

3.4.3 General scour by Blench's method

The Blench's regime depth is given by the expression,

$$R = 1{,}23\left(\frac{q^{2/3}}{d_{50}^{1/12}}\right) \quad ...(6)$$

3.4.4 General scour by critical shear velocity method

This method is based on the assumption of uniform flow during regime condition. The critical shear velocity is a function of d_{50} [1] and is given by,

$$u_{*c} = 0.0115 + 0,0125\,(d_{50}) \qquad \text{...(7)}$$

The flow depth from water surface to the mean scoured depth by critical shear velocity method is given by,

$$R = \frac{{u_{*c}}^2}{gS_0} \qquad \text{...(8)}$$

where, S_0 is the channel slope; and
g is the acceleration due to gravity = 9,81m/s^2

3.4.5 General scour by critical average flow velocity method

In this method, the discharge for scour depth is expressed as,

$$Q = \mathrm{W\,R}\left\{u_{*c}\, 5{,}75 log\left(\frac{5{,}53\,R}{d_{50}}\right)\right\} \qquad \text{...(9)}$$

where, R is the flow depth from water surface to the mean scoured depth considering live-bed condition and is iteratively computed given the discharge, shear velocity, and d_{50}.

3.4.6 General scour by Maza Alvarez and Echavarria Alfaro method

In this method, the flow depth from water surface to the mean scoured depth considering live-bed condition is given by,

$$R = 0{,}365\left\{\frac{Q^{0{,}784}}{\left(W^{0{,}784} d_{50}^{0{,}157}\right)}\right\} \qquad \text{...(10)}$$

In the present case study, from equations (1), (6), (8), (9), and (10), the following general scour depths (R) have been estimated as tabulated below.

Table 4: General scour depths (R) from various empirical methods

Empirical method	R	Unit
Lacey's waterway method	18,44	m
Blench method	8,73	m
Critical shear velocity method	0,24	m
Critical average flow velocity method	36,79	m
Maza Alvarez and Echavarria Alfaro method	12,10	m

3.4.7 Conclusion to general scour estimate

It is to be noted from Table 4 that the general scour estimated from the critical shear velocity method is too low and hence, it is ruled out for any consideration. Finally, the general scour for the project has been estimated as the average of R values obtained from other four methods mentioned in the table. As a result, the final general scour works out to be 19,01m and is denoted by bold letter **R,** such that **R** = **19,01m.** The details of the computations of the general scour have been furnished as Annexure 1 (sheet 1 of 2).

3.4.8 Contraction scour depth

Contraction scour can occur due to approach embankments to the RO-RO ramp, which may cause some flow to get diverted towards the adjacent channel or main channel of the river. In the present case, as the RO-RO ramp terminates in the floodplain, the structure is similar to an abutment with long approach embankment except the fact that it passes the flood, whereas the embankment does not. But in both the cases, the deviation of flow towards other channels is likely. Hence, the case of abutment in flood plain for live-bed is adopted to assess the contraction scour.

Initially the competent velocity method (Neill, 1987) is employed to determine whether contraction scour is possible to occur in the flood plain. The competent velocity (V_c) is the average velocity for a channel flow that does not erode the bed. The set of transformed equations [8] developed for the competent velocity curves presented by Neill have been elaborated below.

For $d_{50} \geq 0{,}03\text{m},\ V_c = 6{,}35 y_{fp} d_{50}^{0{,}333}\ m/s$ ...(11)

For $0{,}03\text{m} > d_{50} > 0{,}0003\text{m},\ V_c = 4{,}16\, y_{fp}^{\propto}\, d_{50}^{0{,}25}\ m/s$ ...(12)

where, exponent $\propto = \dfrac{0{,}125}{d_{50}^{0{,}18}}$

For $0{,}0003\text{m} \geq d_{50},\ V_c = 0{,}55 y_{fp}^{0{,}5}\ m/s$ ...(13)

The standard contraction scour depth for live-bed [1] is given by,

$$d_{sc*} = y_{ch}\left[\left(\frac{Q_2}{Q_m}\right)^{6/7}\left(\frac{W_1}{W_2}\right)^{k_1}\right] \qquad \text{...(14)}$$

However, as the adopted case is for pseudo-abutment, the above equation changes to:

$$d_{sc*} = y_{ch}\left[\left(\frac{Q_2}{Q_m}\right)^{6/7}\left(\frac{W_1}{W_2}\right)^{k_1} - 1\right] \quad \text{...(15)}$$

where, Y_{ch} = flow depth in the main channel;

Q_2 = flow through the berthing structure (assuming the structure spanning the banks of the river);

Q_m = flow through the main channel;

W_1 = bottom width of the main channel; and

W_2 = bottom width of the berthing structure (assuming a bank to bank bridge span)

During HFL, the ratio $W_1/W_2 = 1$. In the present study, the contraction scour has been estimated to be 0,09m. The contraction scour, here, represents the scour in the main channel, which is negligible. However, to be conservative, for design purposes, allowance of contraction scour in the floodplain is given by considering the aforesaid contraction scour as the final contraction scour for project works and is given by,

$$d_{sc*} = 0{,}09\text{m} \quad \text{...(16)}$$

The details of the computations of contraction scour have been furbished as Annexure 1 (sheet 1 of 2).

3.4.9 Local scour depth

Local scour is caused by the interference of the piers and abutments with the flow [1]. It occurs at the immediate vicinity of these structures. The live-bed condition has been considered for the computation of local scour. The live-bed scour occurs during sediment transportation in a river. The equilibrium scour depth is reached when the time-averaged transport of sediments entering the scour hole equals the removal of sediment from it. The equilibrium local scour depth [1] is given by,

$$Y_s = K_y K_s K_\theta K_G K_I K_d \quad (17)$$

where, K_y is the depth-size factor; K_s is the shape factor; K_θ is the alignment factor; K_G is the approach channel geometry factor; K_I is the flow intensity factor; and K_d is the sediment size factor.

The depth-size factor is given by,

$$K_y = 2{,}4\, b_s \quad \left(if\ \frac{b_s}{y_0} < 0{,}7\right) \quad \text{...(18)}$$

$$K_y = 2\sqrt{y_0\, b_s} \quad \left(if\ 0{,}7 < \frac{b_s}{y_0} < 5\right) \quad \text{...(19)}$$

$$K_y = 4{,}5 y_0 \quad \left(if\ \frac{b_s}{y_0} > 5\right) \quad \text{...(20)}$$

where, b_s is the representative length or diameter of the pier; and y_0 is the water depth upstream of the pier.

In the present case study, the pier shape is circular of cylindrical type. Hence, the shape factor, $K_S = 1$ and the alignment factor, $K_\theta = 1$ [1]. As the equivalent rectangular channel of the river would insignificantly alter the hydraulic properties of it during a HFL condition, the approach channel geometry factor, $K_G = 1$ is adopted. The flow intensity factor, K_I and the sediment size factor, K_d are normally 1 as per the laboratory findings.

The factor of safety (FS) is applied to best-fit the prediction of local scour depth and recommended value of FS = 1.6 (Johnson, 1992) [2] has been adopted. The maximum local scour depth is given by,

$$d_{sloc} = FS.Y_s \quad \text{...(21)}$$

Applying the above equations, the maximum local scour depth of the RO-RO ramp piers has been estimated to be 5,38m. The details of computations have been displayed in Annexure 1 (sheet 2 of 2).

3.4.10 Total scour depth

The total scour depth is the accumulation of all possible types of scour that is anticipated on a river site of interest. The present case study considers the general scour, contraction scour, and the local scour as predominant in the evaluation of the total scour depth. Therefore, the total scour depth (d_{stot}) has been computed by summing up the aforesaid scour depths as,

$$d_{stot} = R + d_{sc*} + d_{sloc} \quad \text{...(22)}$$

From the above, the total scour depth has been estimated to be 24,48m to be considered below the HFL. Hence, the deepest scour level for design purposes have been recommended to be 8,12masl and the computed total scour depth is considered as design scour depth for the project. The details of computations have been displayed in Annexure 1 (sheet 2 of 2).

4. Discussion, conclusions, and acknowledgements

The case study of estimation of scour depth for the RO-RO ramp at Sahibganj, Jharkhand on Ganga River delivers the scour depth estimate with a conservative approach that is widely used. The types of scour may be many [1] but largely, the general scour, contraction scour, and the local scour cover the maximum possible occurrence of scour at the area of interest. Therefore, by examining the present case, these three types of scour have been considered for the determination of design scour depth. The steady-state hydraulic modelling of the Ganga River for the Sahibganj reach is attempted to understand the water surface profile along the reach, where the RO-RO is proposed at a certain location. The representative cross-sections have been examined to obtain the hydraulic properties at any fragment of the sections, thereby determining the floodplain discharge at HFL. The mentioned scours are estimated referring to [1] and [2], thereby finally computing the total scour depth using equation (22); which is an accumulated sum of the general scour, contraction scour, and local scour. Although the applied methodologies are conservative, they are reasonable and the equations used in the estimation of local scour and contraction scour have evolved from the experimental studies and research [1,9] to understand the physical process behind the development of scour apart from the regime theories [1][2] for general scour estimation. In conclusion, the estimation of the total scour depth is an additive process, which means that it is the sum total of all the considered scours in the case study.

It is recognized that the application of 2-dimensional and 3-dimensional physically-based models for scour estimates is vital, especially when the interest of study is localized. Also, the hydroinformatics techniques to analyze the scour are worthy to be applied. In the present case study, due to project constraints, such alternatives have been anticipated for future research works. However, in recent practices, the desiderata for estimation of scour depth are the hydraulic modelling of bridges and are recommendable.

I express my very great appreciation to Dr. S.K.Mazumder for his valuable and constructive suggestions on the topic of bridge scour at various occasions of discussion. I am thankful to Mr. Prithiviraj Mitra and Mr. Vivekanand Pokhriyal, who extended their help in data collection and data organization during the project works.

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Design scour depth at RO-RO Ramp (Berthing Structure Piers) **Annexure 1 (sheet 1 of 2)**

A. General scour depth

a) General scour by Lacey's waterway method

Discharge for scour depth, Q=1* Q			90096	m^3/s
Actual waterway		L=	6040	m
Regime width of stream		W=	2161,15	m
	2,4 b_s	L/W=	2,79	
Depth of water in river		y=	22,43	m
Discharge intensity in m^3/s per metre width	4,5 y_0	q =	41,69	$m^3/s/m$
Median size bed material		d_{50}=	0,15	mm
		d_{50}=	0,00015	m
Silt factor K_{sf} = 1·76√ d50		K_{sf} =	0,68	

For L/W >= 1, the normal scour depth below HFL from Lacey's equation,
R= 1.35 * {(q^2)/K_{sf})}^(1/3) R = 18,44 m

b) General scour by Blench's method

Discharge for scour depth		Q =	90096	m^3/s
Full bank width		W' =	6040	m
Discharge intensity in m^3/s per metre width		q =	14,92	$m^3/s/m$
Blench's regime depth	R =1.23($q^{(2/3)}/d_{50}^{(1/12)}$)	R =	8,73	m

c) General scour by Critical shear velocity method (uniform flow)

Critical shear velocity	*(u_{*c} = 0.0115+0.0125*d501.4)*	u_{*c} =	0,0115	m/s
Shield's parameter (critical)	(θ_c = u_{*c}2/(Ss-1)gd50)	θc =	0,054	
Channel slope		S_0 =	0,00057	m/m
Flow depth from water surface to mean scoured depth	R=(u_{*c}2/gS_0)	R =	0,024	m

d) Critical average flow velocity method

Discharge for scour depth		Q =	90096	m^3/s
Discharge for scour depth	Q = W*R*(u_{*c}5.75log(5.53R/d50)	Q =	90096	m^3/s
Flow depth from water surface to mean scoured depth		R =	36,79	m

e) Maza Alvarez and Echavarria Alfaro

Discharge for scour depth	Q =	90096	m^3/s
Flow depth from water surface to mean scoured depth,	R =	12,10	m

R = 0.365(Q0.784/(W0.784d500.157)

General scour depth (average), R = 19,01 m

B. Contraction scour depth

	d_{50}	=	0,15	mm	0,00015 m
High flood level in the river	HFL	=	32,6	m	
Bed level in the channel	BL_c	=	10,17	m	
Lowest bed level in the flood plain	BL_{fp}	=	21,5	m	
Flow depth in the flood plain	y_{fp}	=	11,1	m	
Flow depth in the channel	y_{ch}	=	22,43	m	
Exponent	α	=	0,61		
Competent velocity	V_c	=	1,83	m/s	
Design flood	Q_D	=	90096	m^3/s	
Discharge through floodplain	Q_{fp}	=	431,30	m^3/s	(from HEC-RAS results)
Floodplain width	W_{fp}	=	390	m	(from HEC-RAS results)
Floo plain velocity	V*	=	$Q_{fp}/W_{fp}y_{fp}$	m/s	
Floodplain velocity	V*	=	0,10	m/s	< V_c => Contraction scour is unlikely in the floodplain
For channel flow through the berthing structure peirs					
Total discharge through berthing structure	Q_2	=	90096	m^3/s	(assuming the structure spanning the banks of the river)
Discharge through main channel	Q_m	=	89664,7	m^3/s	

Contraction Scour, d_{sc}
$$= y_{ch}\left[\left(\frac{Q_2}{Q_m}\right)^{6/7}\left(\frac{W_1}{W_2}\right)^{k_1}-1\right] \quad \text{(live-bed)}$$

W_1 = Bottom width of the main channel (m)
W_2 = Bottom width of the berthing structure section {assuming a bank to bank bridge}(m)
But during HFL, W_1 ≈ W_2 => W1/W2 = 1

Contraction Scour, d_{sc} = 0,09 m

Design scour depth at RO-RO Ramp (Berthing Structure Piers) — Annexure 1 (sheet 2 of 2)

C. Local Scour

Local Scour Depth (equilibrium) $Y_s = K_y{*}K_s{*}K_\theta{*}K_G{*}K_I{*}K_d$

Maximum Local Scour Depth $d_{sloc} = FS{*}K_y{*}K_s{*}K_\theta{*}K_G$

K-Parameters

1) Depth-size factor, K_y

$K_y = 2{,}4\ b_s$ (for $b_s/y_0 < 0.7$)

$K_y = 2\ (y_0 b_s)$^0.5 (for $0.7 < b_s/y_0 < 5$)

$K_y = 4{,}5\ y_0$ (for $b_s/y_0 > 5$)

where, b_s is the representative length or diameter of the pier

y_0 is the water depth upstream of the pier

2) Shape factor, K_s

Shape = Circular

$K_s = 1$

3) Alignment factor, K_θ

Type = Circular

$K_\theta = 1$

4) Approach channel geometry factor, K_G

$K_G = 1$

5) Flow intensity factor, K_I

$K_I = 1$

6) Sediment size factor, K_d

$K_d = 1$

Design of Maximum Local Scour Depth

b_s	=	1,40	m
y_0	=	11,10	m
b_s/y_0	=	0,1	
Depth-size factor, K_y	=	**3,36**	
Shape type	=	**Circular**	
Shape factor, K_s	=	**1,00**	
Alignment factor , K_θ	=	**1,00**	
Approach channel geometry factor, K_G	=	**1,00**	
Factor of safety, FS	=	**1,6**	
Local Depth of Scour, d_{sloc}	=	**5,38**	**m**

D. Total Scour Depth

HFL	=	32,6	masl
Natural/ General Scour Depth	=	19,0	m
Contraction Scour Depth	=	0,1	m
Local Scour Depth	=	5,4	m
Lowest river bed level at the pier of the berthing structure	=	21,5	masl
Hence, the deepest scour level	=	**8,1**	**masl**
Total Scour Depth below HFL	=	**24,5**	**m**

Note: If the rock level is above the deepest scour level under the structure, then the foundation level of the structure shall be adjusted according to the rock level.*