Analysis and Estimation of local scour around bridge piers using modified HEC-RAS programming tool

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Abstract
The western part of Tripura in India due to its geographical location and topography, is under constant risk of rainfall-driven flash floods occurring in the Gumti River causing colossal damage to life and properties almost every year. In this view, an analysis of the scour depth around bridge piers for its safety against the scouring is necessary for mitigating such flood hazards. In this study, we have used a modified HEC-RAS programming tool (HEC-RAS version 5.0.7, March 2019) to develop a scour model for evaluating the maximum local scour depth around bridge piers. We have selected three major bridges namely Subash Sethu, Burima bridge and Machmara bridge on the river Gumti and collected various dimensions of the bridge, scour profiles, sediment properties, etc. and also daily discharge data during 1980 to 2010 from Gomati Barrage Subdivision, Udaipur. Our model is calibrated using several empirical scouring models and it was found that the calculated scour depth from the HEC-RAS software is consistent with other models such as CSU, Larras and Ahmed.

The dimensionless analysis is also used to determine the correlation among scour depth (d_s) and flow depth (y), Froude number (F_r), angle of attack (θ) and contraction ratio (C_r). In the present study, it is found that an increase in the angle of attack by 3° results in an increase in the scour depth of 12.06%, 43.75% and 22.27% for 2-span, 3-span and 4-span bridges respectively. This study also found an increase in scour depth with increasing pier diameter. Overall, the HEC-RAS modeling tool works well in predicting scour depth in all three bridges and the estimated results are in line with other empirical models.

Keywords: Bridge piers, Contraction scour, Local scour, Scour depth, HEC-RAS.

Introduction

Bridges are significant structures that require a large investment to construct and it is necessary to protect these structures by constant monitoring and maintenance[12]. Highway and railway transportation networks rely heavily on bridges. It is well-known that bridge piers are particularly sensitive to natural and man-made disasters such as earthquakes and flooding. Transport networks can be severely disrupted if bridge piers are damaged as a result of catastrophic occurrences, resulting in considerable economic losses for society. Because of this, the safety and serviceability of bridges are always placed on high priority.

When water flows through a bridge, in that case, scour can be defined in such a way that it is nothing but the erosive action of the running water, when it excavates the sediment from the bed or banks of the river bed due to the interaction of the structures such as bridge pier, abutments on the flowing water[8]. The main characteristic feature of the flow is a relatively large secondary vortex flow within the scour hole and skewed velocity distributions along the circumference of the pier[5]. The separation of the upstream incoming boundary layer and the development near the bottom of necklace-like vertical formations are known as horseshoe vortices which stretch around the pier and bend over its upstream portion as a result of the pier. If the upstream flow is turbulent, these vortices are highly variable in time[14]. The vortices cannot be prevented by the local scouring control device linked to the cylinder[4]. If the upstream flow is turbulent, the location, size and intensity of these vortices are highly variable in time.[9]

In alluvial stream, continuous transportation of sediment can be seen as a geo-morphological process. If something disrupts this sediment transportation process by constructing barrages, dams etc., it may cause long-term changes in the stream bed evaluation[2]. Due to the continuous sediment transportation, if the river bed increases, then it is called aggradations and in an opposite way, due to the erosion if the river bed decreased day by day, then it is called degradation. But in total, scour aggradations do not have any contribution[25]. In 1930 Lacey's regime formula was developed with very limited field data in the Ganga River considering the waterway ranged between 3.6 km to 2 km[15]. The study revealed that the width of the waterway has effects on the abutment scour and the contraction scour. Another study suggested that the angle of attack is also a significant factor that affects the local scour around any pier.[28]

Melville et al[16] investigated the scour depth for several bridges and concluded that an equilibrium scour is influenced due to three factors: angle of attack, the particle size of sediment and flow depth. Another study reported that the local scour rises significantly with the number of piers[18].

Dey et al[5] explored the 3D unsteady semi-vortex flow in and around circular abutments. In a study on the local scour around bridge piers using the Bridge Stream Tube model for Alluvial River Simulation model in some major river systems in Iran, the scour depth fits in the best agreement up to a pier diameter of 2 m[26]. The HEC-RAS modeling tool is used to estimate the local scour in restricted water way[3].

Khassaf et al[11] computed scour depth using HEC-RAS around Al-Kufa bridge piers which were in line with the observed value. Mousavi et al[18] evaluated various factors affecting the scour depth using the HEC-RAS tool and CSU model. It was found that the output from the CSU equation gave acceptable results with the HEC-RAS model. Ghaderi et al[7] found that the Frohlich approach is less vulnerable to changes in discharge than the CSU method in a case study of Simineh Rood Bridge, Iran.

Kumar et al[13] did a replication of flow behavior in and around circular piers using computational fluid dynamics and the findings were in line with the empirical model. Ahmadianfar et al[1] used a novel AI approach to predict local scour under the combined action of wave and current and the proposed algorithm gave a highly accurate prediction of scouring depths.

Elsebaie[6] proposed a probabilistic approach to estimate scour depth by assigning a precedence factor with flow rates and scour depths generated by the HEC-RAS model.

Silvia et al[24] studied scour depth around circular piers with the HEC-RAS tool (version 5.7) and the results showed a maximum scour depth of 5.04 m. Some of the most recent studies for the prediction of scouring have used GA, ANN, Wavelet model, Hierarchical clustering etc. Seifollahi et al[22] estimated the local scour from a cylindrical pier considering several flow parameters using a Wavelet model compiled with ANN.

Rasoul et al[21] studied local scouring of bridge piers using experimental study and ANN, ANFIS algorithms. Recently, Oguz et al[20] used an adaptive Genetic Algorithm for the estimation of local scour around semi-circular abutments.

The literature review suggests that various researchers have studied scour models in different fields and the scour can be computed in Lacey's regime formula[28], BRI-STAR model[26], HEC-RAS software[3,18], Hierarchical Clustering and Adaptive Genetic Programming[20] etc. Local scour depth depends on various factors like flow depth, Froude number, Reynolds number, contraction ratio, angle of attack pier diameter etc[16].

The mechanism of scouring over different bed conditions is very sensitive but the variations of scouring are mainly affected by variables like the angle of attack and pier diameter. Several river cross-section data and various soil parameters are needed for the computation of scouring.

The western part of Tripura, due to its geographical location and topography, is under constant risk of rainfall-driven flash floods occurring in the Gumti River, which causes colossal damage to life and properties almost every year. In this view, a study for the prediction of local scouring depth around bridge piers for its safety against the scouring is necessary for mitigating such flood hazards.

Thirty years' daily discharge data for Gomati River is collected from Gomati Barrage Subdivision under Water Resource Division, Udaipur ranging from 1980 – 2010. The graphical representation of the yearly maximum discharge is shown in fig. 1. Some other data like the cross-section of the river at various intervals, HFL, LBL, water depth, etc. are also collected from this division.

In the present study, different hypothetical models are developed in the HEC RAS modeling tool and local scour is found for three bridge locations on the Gomati River. Flow depth (y), Froude number (F_r), angle of attack (θ), contraction ratio (C_r), Pier diameter (D) and angle of attack are taken as input variables.

Study Area and Data Collection

We have selected three major bridges on the River Gumti in the present study. The Gumti River is the largest in the north-eastern Indian state Tripura state which originates from the mountain range connecting Longtharai and Atharamura. The river runs across the southwestern part of Tripura stretching from west to east of the State and then flows towards Bangladesh by the side of Sonamura town.[27] It is located between latitudes 23º19′ and 23º47′ N and longitudes 91º14′ E and 91º58′ E.

As mentioned earlier, three bridge sites were considered in the study, first location is selected near the North Machmara in Tripura. The bridge is between Pecharthal and Kanchanpur. The latitude of Pecharthal is 24˚19´N and longitude is 92˚10´E and the latitude of Kanchanpur is 24˚03´N and longitude is 92˚20´E.

The second location is selected near Bishalgarh in Tripura. The bridge is between Golaghati and Takarjala. The latitude of Golaghati is 23˚67´N and longitude is 91˚37´E and the latitude of Takarjala is 23˚70´N and longitude is 91˚41´E.

The third study is located in Udaipur in Tripura. The latitude and longitude of Udaipur are 23° 31' N and 91° 31' E respectively. This bridge is connecting Assam-Agartala NH 8.

Sieve Analysis: Particle size of the sediment plays an important role in scour analysis. Scour depth increases with the decrease of sediment size. Grading of soil is a great matter of concern in sediment analysis. In the present study, sediment sample was collected from the three bridge sites using the auger. Dry sieve analysis is carried out for Burima and Subhas Bridge sight sediment sample and wet sieve analysis is done for the Machmara Bridge sight sediment sample and the results are shown in fig.5 (a), (b) and (c) and d_{50} value is calculated for analysis of scour in HEC-RAS modeling tool.[23]

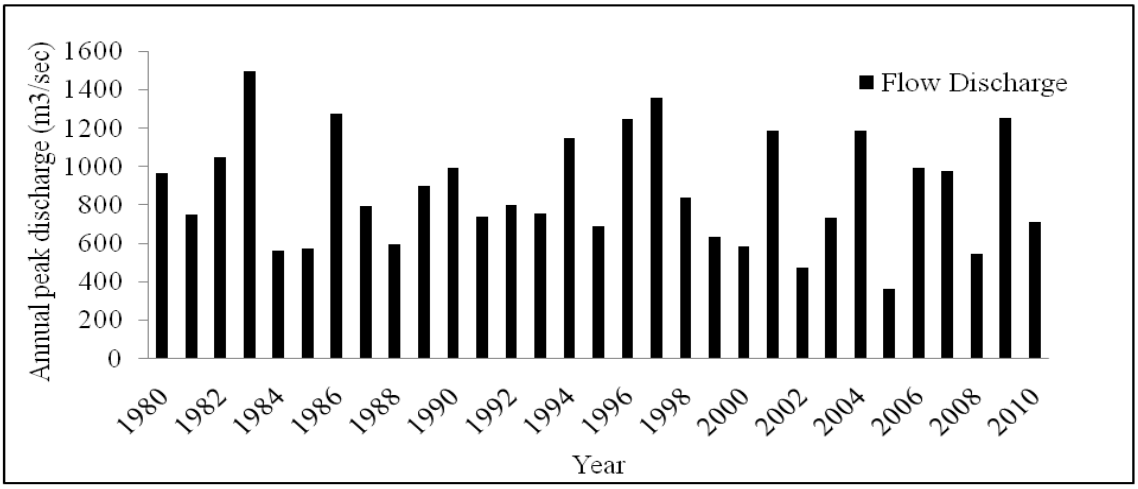


Figure 1: Peak discharge data of Gomati River for the period 1980 – 2010

Figure 2: Pictorial view of Machmara Bridge

Figure 3: Pictorial view of Burima Bridge

Theoretical Background

Maximum pier scour depths may be predicted using the Colorado State University (CSU) equation for both live-bed and clear-water pier scour. The scour depth (y_s) is estimated as follows:

$$y_s = 2.0\ C_1 C_2 C_3 C_4 b^{0.65} {y_1}^{0.35} {F_r}^{0.43} \quad (1)$$

where C_1 = shape factor, C_2 = Correction factor for angle of attack, C_3 = Correction factor for bed condition, C_4 = Correction factor for bed material, b = Width of the pier (m), y_1 = Upstream flow depth in meter and F_r = Froude Number.

The Froehlich model is an established model to estimate local scour around a pier and it is given by:

$$y_s = 0.32\varphi(f)^{0.62}{y_1}^{0.47}{F_r}^{0.22}{d_{50}}^{-0.09} + b \quad (2)$$

where φ = Correction factor for the shape of pier nose, f = Pier in the direction of the flow in meters, y_1= depth measured at the upstream side of the pier in meters, F_r = Froude Number and b = width of the pier in the direction of the flow in meter.

The algorithms of CSU (Eq. 1) as well as Froehlich (Eq. 2) are inbuilt into the HEC-RAS modeling tool. So, non-dimensional analysis is done directly from the output data which are produced by the HEC-RAS.

Calibrated Models: In the present study, scour model developed by the HEC RAS tool is compared with some other scour equations.[19] Scour depth (y_s) is estimated as follows:

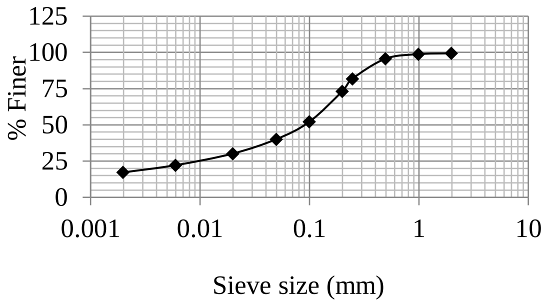
$$y_s = Cq^{2/3} - y_1 \quad (3)$$

where y_1= flow depth at the upstream of the pier or abutment excluding local scour and C = Flow parameter which depends upon the size and shape of the piers, the width of the abutments, angle of attack, the approach velocity and the boundary conditions.

$$y_s = 1.8b^{0.25}q^{0.5}\left(\frac{y_1}{{V_1}^2}\right)^{0.25} - y_1 \quad (4)$$

where b = pier width, q = flow rate per unit width on the upstream side of the river, y_1 = bed factor and V_1 = approach velocity on the upstream side of the river.

Figure 4: Pictorial view of Subhas Bridge



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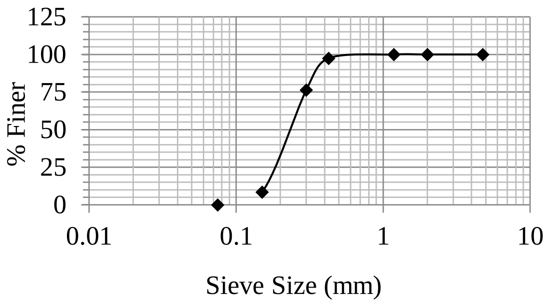

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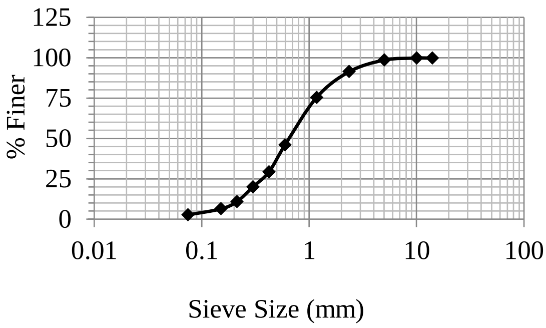


(c)

Figure 5: Particle size distribution for the sediment sample of (a) Machmara Bridge, (b) Burima Bridge and (c) Subhas Bridge

$$y_s = 2.0 y_1 C_1 C_2 \left(\frac{b}{y_1}\right) F_r^{\,0.43} \tag{5}$$

where C_1 = a model parameter which depends upon the shape of the bridge piers, C_2 = a model parameter which depends upon the ratio of the pier length to pier width, y_1 = bed factor, b = the angle of the approach flow referenced to the bridge pier and F_r = Froude number.

$$y_s = 1.42 C_s b^{0.75} \tag{6}$$

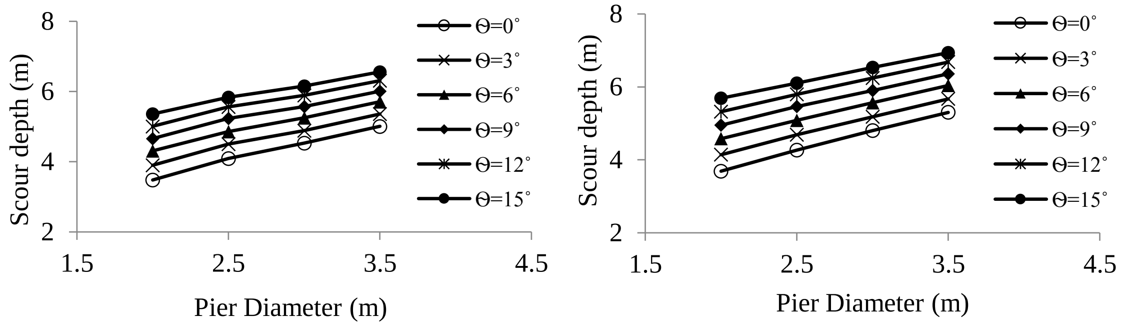
where y_s =depth of flow just up-stream from the bridge pier or abutment excluding local scour, C_s = coefficient based on the shape of the pier nose and b =width of the bridge pier.

$$y_s = 3.4 F_r^{\,0.67} \tag{7}$$

where F_r= Froude number.

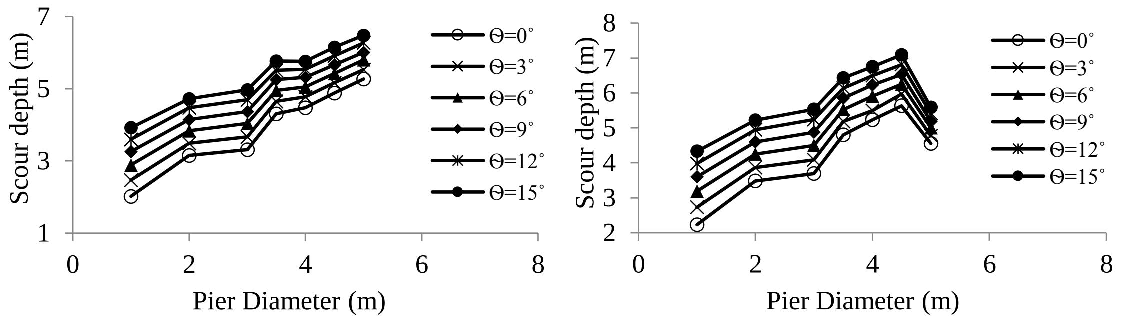
Results and Discussion

Computation of scour depth: Scour depth depends on many factors like discharge, the velocity of flow, water level, angle of attack, pier diameter etc.[6] Present study is considering only discharge, pier diameter and angle of attack as a variable. Figures 6, 7 and 8 show the incremental increase of scour depth with the gradual increase of pier diameter and angle of attack in Machmara, Burima and Subhas Bridge sight. The water passage area decreases due to the increase in pier diameter.



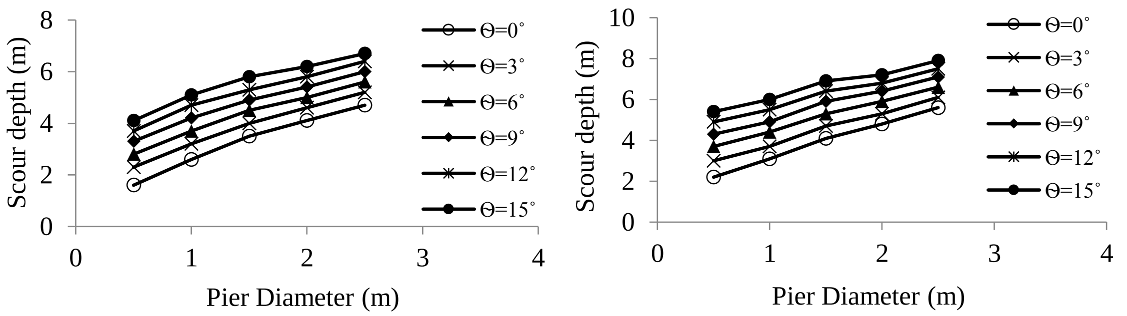
(a) **(b)**

Figure 6: Variation in scour depth with pier diameter for different angles of attack for Machmara bridge (a) full waterway and (b) Restricted waterway



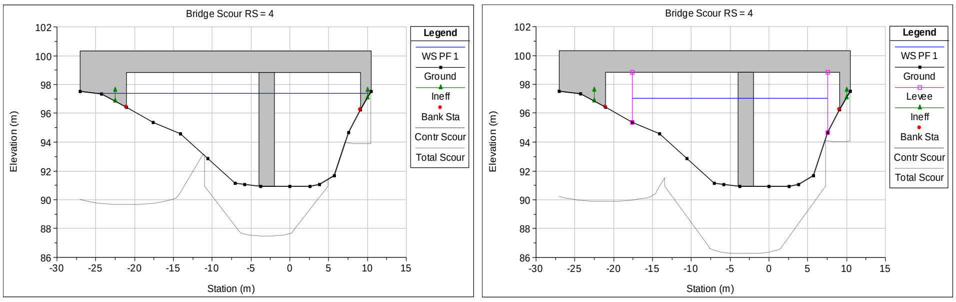
(a) **(b)**

Figure 7: Variation in scour depth with pier diameter for different angles of attack for Burima Bridge (a) full waterway and (b) Restricted waterway



(a) **(b)**

Figure 8: Variation in scour depth with pier diameter for different angles of attack for Subhas Bridge (a) full waterway and (b) Restricted waterway



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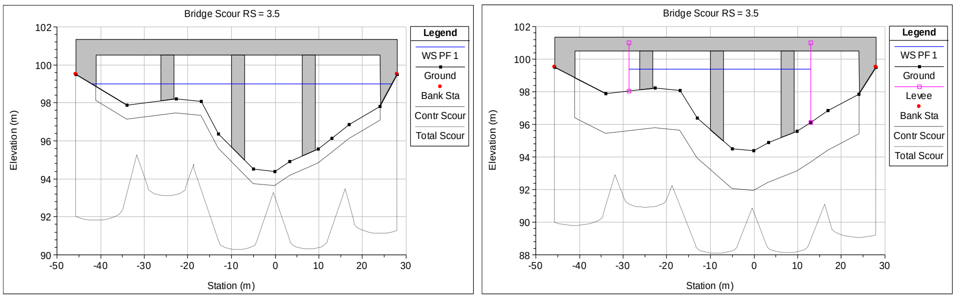

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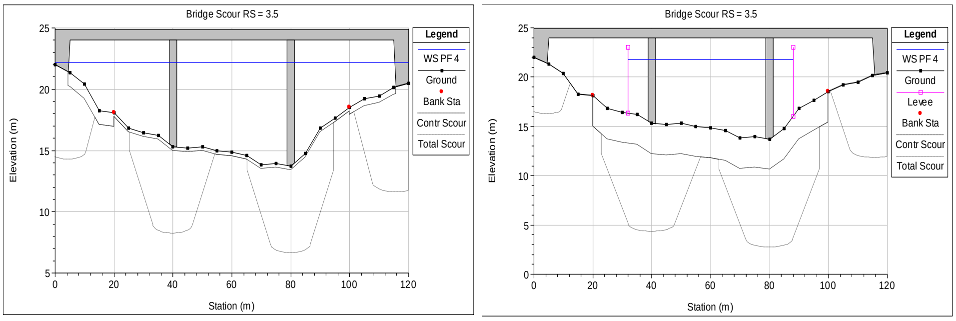

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Figure 9: Scour depth using HEC-RAS tool in (a) Machmara, (b) Burima and (c) Subhas Bridge Sight

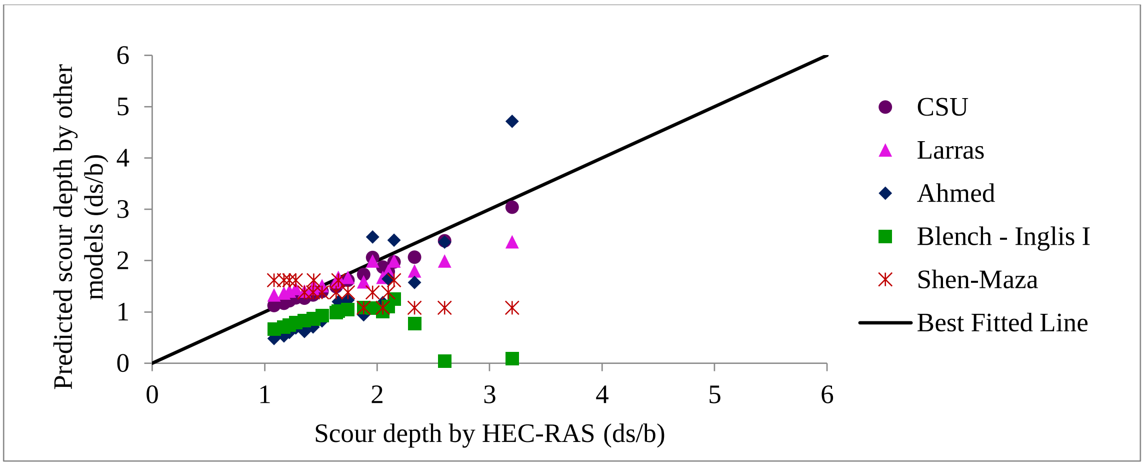


Figure 10: Comparison of predicted scour depth between the HEC-RAS model and other empirical models

As a result, velocity of the flow also increases and results in an increase of local scour around the bridge pier and abutments area of the bridge.

Calibration of scour depth: Mathematical formula for finding out scour depth has been given by many researchers. Nowadays HEC-RAS is used worldwide to find the scour depth[9]. It is more acceptable than the other models[11]. There is a scope for comparing scour depth computed by the HEC-RAS tool with other scour models[10]. In the present study, one statistical analysis is done based on the scour depth. Considering the HEC-RAS model as a standard, a comparison of scour depth between HEC-RAS and the other five models has been presented in the graph shown in fig.10.

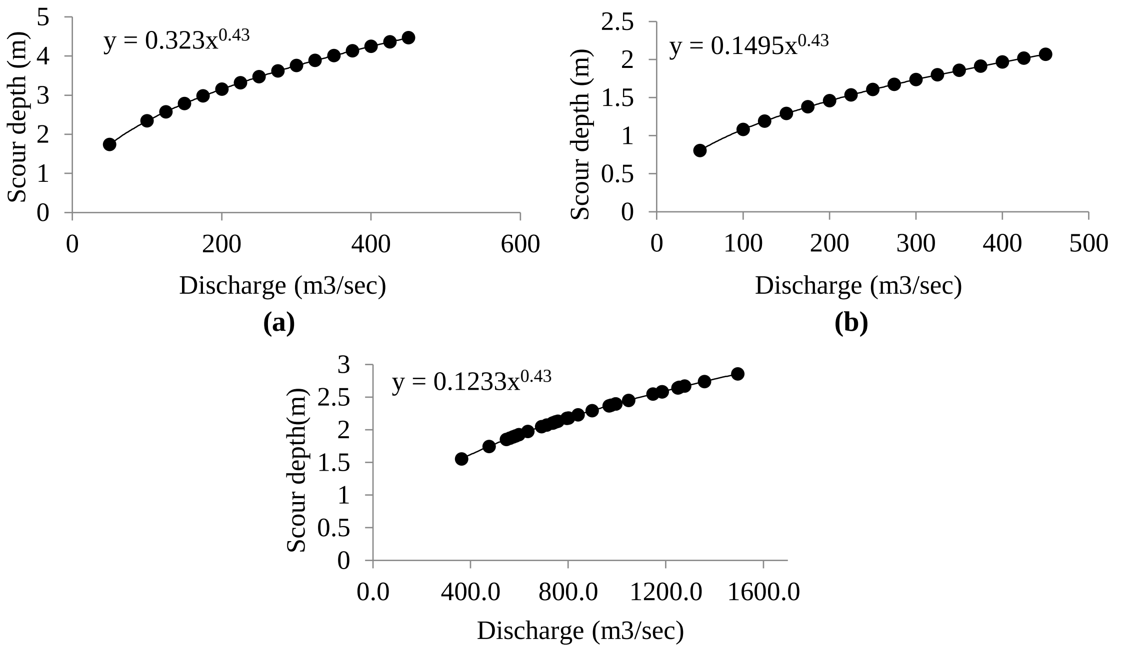
Statistical Analysis: For carrying out a computation, a boundary condition is necessary. The downstream boundary condition is to be considered for subcritical flow and the supercritical flow upstream boundary condition is to be considered. The slope in three of the locations is very low. So while computing the scour depth in the HEC-RAS tool, a lower boundary condition is applied for the subcritical flow. As a result, an increase in scours depth is observed with the increase in discharge which is shown in fig. 11. The graphical plot between the discharge and scour depth is also given in the figure.

Dimensionless Analysis: The dimensionless grouping approach is used to determine the factors impacting the scour depth[17]. To explain the fluctuation of these groups with scouring depth, data generated from the HEC-RAS model is used. Scour depends on many factors. One of them is flow depth. All the variables are made dimensionless by dividing by the pier diameter[5]. Fig. 12 shows the comparison between scour depth and flow depth. It shows that the scour depth increases with the increase in flow depth. The influence of approach velocity is studied by examining the effect of the pier's Reynolds number and the pier's Froude number with local scour depth (Figure 13 and figure 14).

The angle of attack has an appreciable effect on local scour depth. The local scour depth increases by 54.02% when the angle of inclination of the pier was changed from 0° to 15° as shown in fig. 14.

Pier shape and number have a significant effect on local scour depth. The pier number is described by contraction ratio (summation of the openings between piers divided by total channel width). Figures 15 showed the effect of the pier shape and number on the local scour depth.

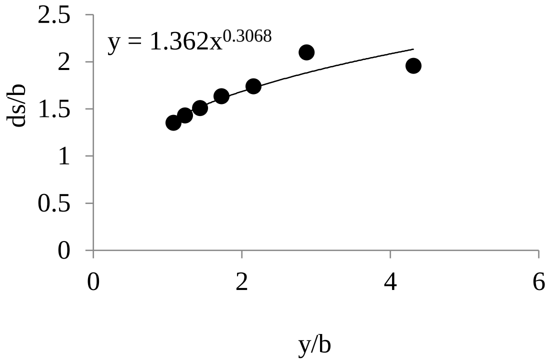
Correlation Analysis: There have been several methods for performing regression analysis. Parametric approaches include linear regression and the ordinary least squares method. In the present study, correlation analysis is done among the HEC-RAS model and other empirical models to verify their linear relationship. Correlations between HEC RAS scour depth and the other seven models are shown in table 1.



(c)
Figure 11: Variation of scouring with discharge in (a) Machmara, (b) Burima and (c) Subhas Bridge

Table 1
Correlation Analysis of the selected models

S.N.	Equation	Correlation factor
1	CSU	0.9975
2	Larras	0.9951
3	Ahmed	0.9961
4	Blench-Inglis	0.8905
5	Shen - Maza	0.9241
6	Inglis-Poona	0.9182
7	Froechlich	0.8739



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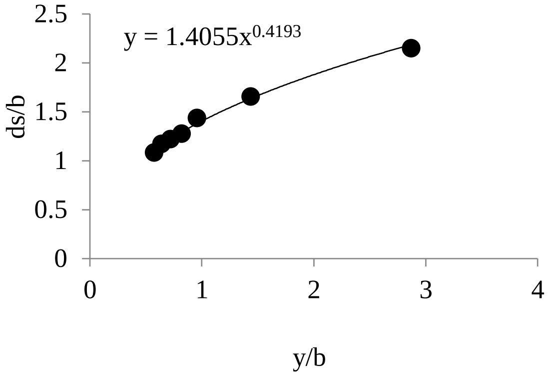

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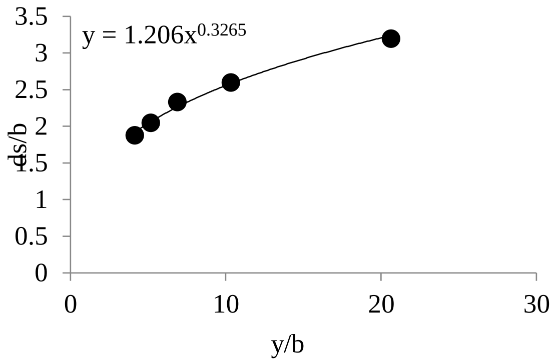

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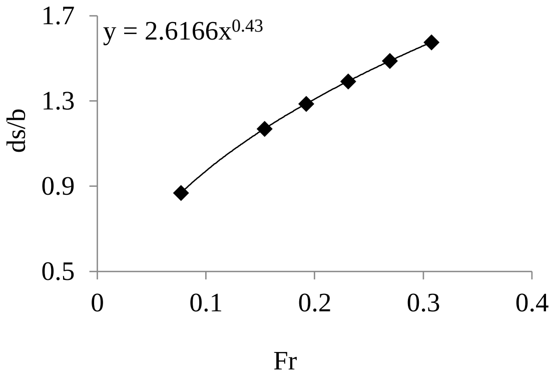
Figure 12: Variation of scouring with flow depth in (a) Machmara, (b) Burima and (c) Subhas Bridge



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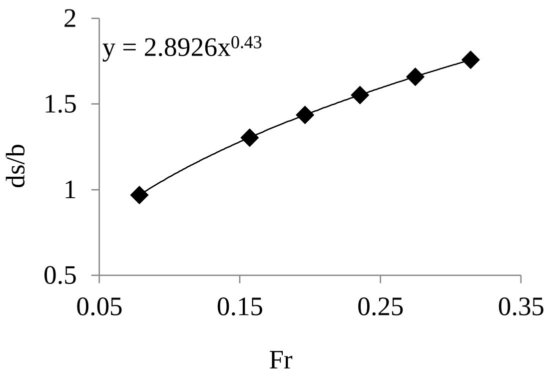

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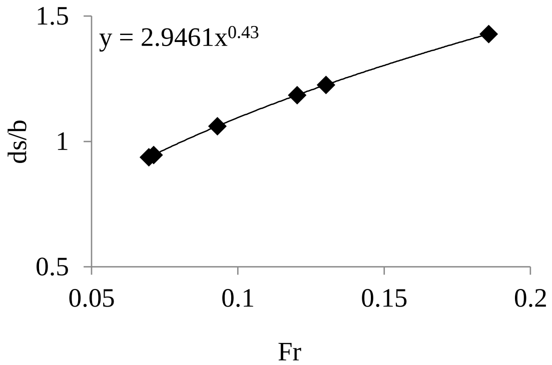

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Figure 13: Variation of scouring with Froude number in (a) Machmara , (b) Burima and (c) Subhas Bridge

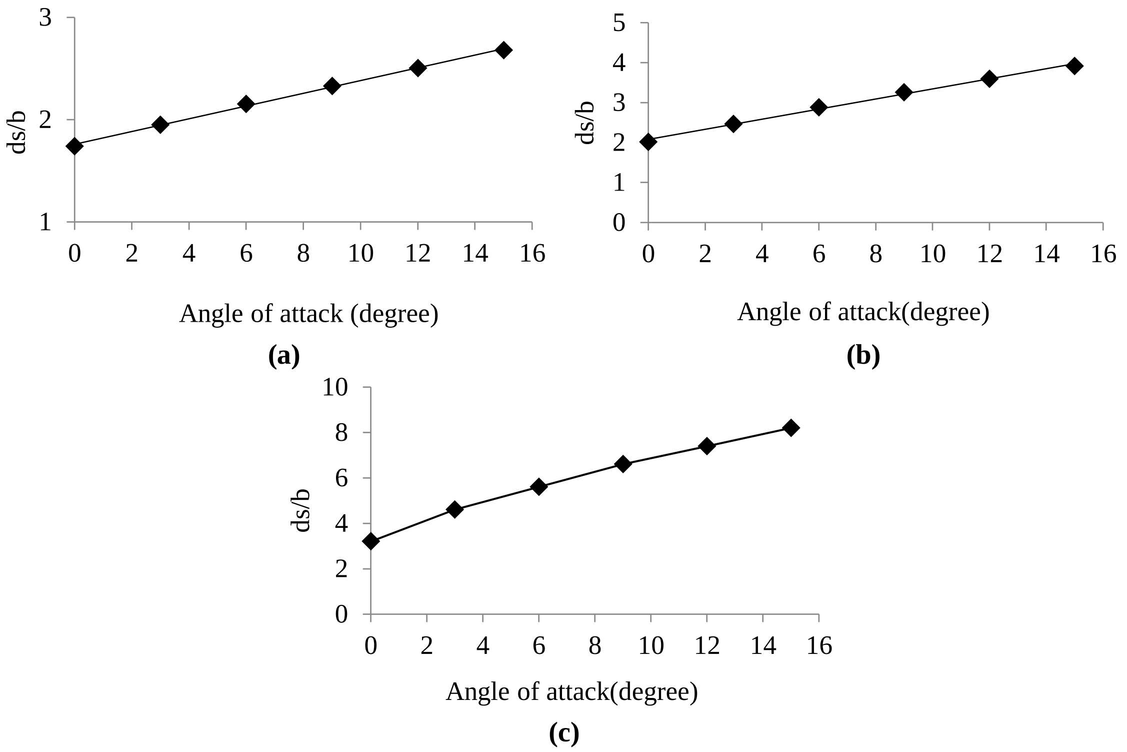

Figure 14: Variation of scouring with the angle of attack in (a) Machmara, (b) Burima and (c) Subhas Bridge

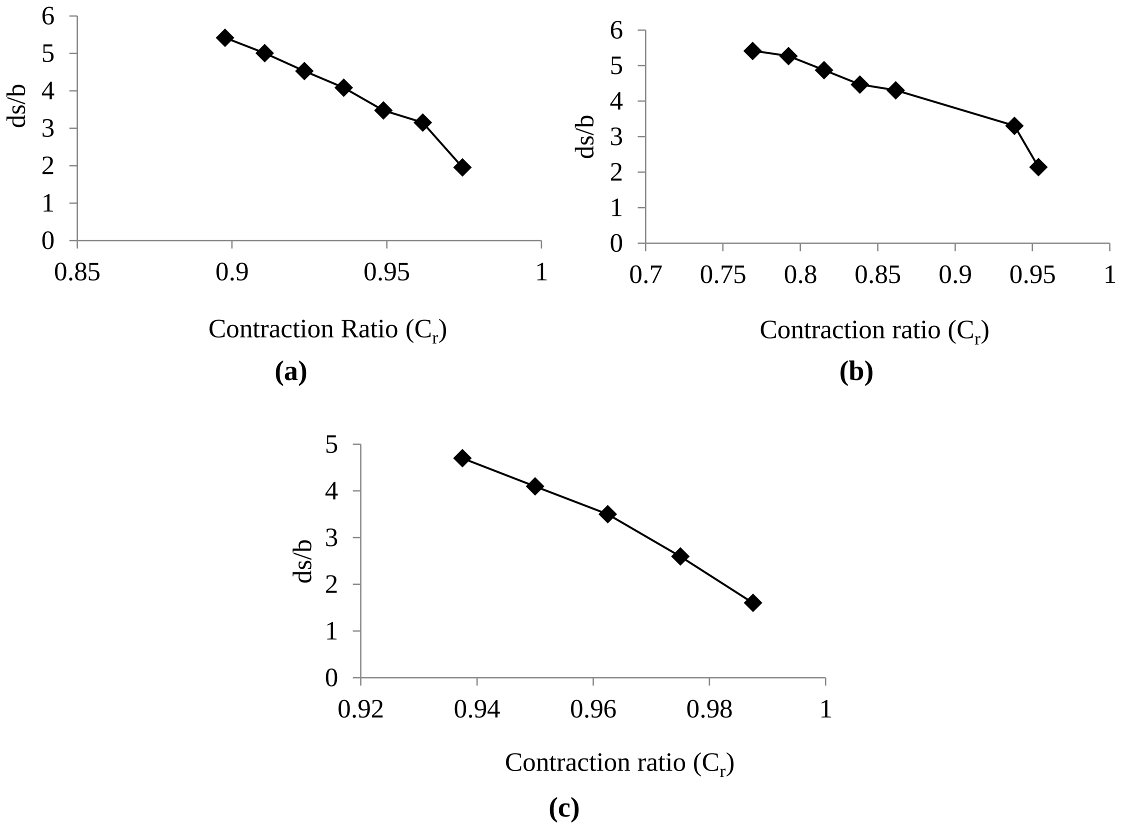

Figure 15: Variation of scouring with contraction ratio in (a) Machmara, (b) Burima and (c) Subhas Bridge

Conclusion

Scour depth analysis is necessary for the study of river morphology, safety and stability of bridge piers on a river. In the present study, we have estimated scour depth using the HEC RAS modeling tool and also compared it with five different empirical models. Some of the major observations are:

1. In the present study, it is found that an increase in the angle of attack by 3˚ (degree) increases the scour depth of 12.06%,

43.75% and 22.27% for 2-span, 3-span and 4-span bridges respectively. Also, it is observed that the scour depth increases with an increase in the pier diameter.
2. On the contrary, scour depth of the selected bridge piers increases up to 37.5% when the width of the cross-section of the river decreases by 33%.
3. Scour depth computed by the HEC-RAS modeling tool is similar to (a) CSU (1975), (b) Ahmed (1953) and (c) Larras (1963) and the correlation between all these models and the computed scour depth from the HEC-RAS model is strongly correlated with CSU (1975) model.
4. Local scour depth increases as discharge increases. With the increase of flow depth and Froude number, local scour depth increases. The scour depth, on the other hand, falls when the river's contraction ratio increases.
5. After analysis of all the hypothetical models, it is observed that the scour depth shows an increase with increasing pier diameter and angle of attack.

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