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# LOCAL SCOUR VARIATION AT PARALLEL BRIDGES A CASE STUDY ON GOLAGHATI BRIDGE, TRIPURA, INDIA

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## ABSTRACT

Bridge pier scour poses a significant risk to hydraulic infrastructure, often leading to structural instability and failure. This study presents a comprehensive numerical simulation of local scour around bridge piers in the Wardha River using the HEC-RAS (Hydrologic Engineering Center's River Analysis System) model. The research aims to evaluate the scour depth under varying hydrodynamic conditions by simulating both historical and design flood events. A detailed geometric model of the study reach was developed, incorporating bathymetric and hydraulic data. The model was calibrated and validated using observed water surface elevations and discharge measurements. Results indicate a strong correlation between discharge magnitude and scour depth, with peak scouring occurring during high-flow regimes. A parametric analysis revealed the influence of pier geometry, flow velocity, and sediment characteristics on scour formation. The findings underscore the utility of HEC-RAS in predicting localized scour and demonstrate its applicability in river engineering and bridge design. This work contributes to improved flood risk management and safer hydraulic infrastructure planning.

**Keywords**: Local scour, Parallel bridges, Burima River, HEC-RAS model.

## INTRODUCTION

Safety and serviceability of the hydraulic structures have always been an issue to the practice and profession of civil engineering (Kothyari, 2007). When water flows through a riverbed, it removes and carries away sediment from the bed and the banks (Meguenni and Remini, 2008; Meddi, 2015; Mfoutou and Diabangouaya, 2019; Bougamouza et al., 2020). This process is influenced by the presence of structures like bridge piers and abutments, as demonstrated by Ghorbani (2008). Scouring can be defined as the product of erosive action of the flowing water. Dey et al. (1995) highlighted key flow characteristics, including a large secondary vortex within the scour hole and uneven velocity distribution around the pier's circumference. Accurate flow measurement in open channels is crucial for predicting local scour, as it enables precise estimation of hydraulic conditions that influence sediment transport and erosion around hydraulic structures (Achour et al., 2024). Accurate flow measurement in open channels is crucial for predicting local scour, as it enables precise estimation of hydraulic conditions that influence sediment transport and erosion around hydraulic structures (Achour et al., 2024a; Achour et al., 2024b). Experimental studies on modified flumes and channel control devices have significantly improved the accuracy of such measurements, especially under varied flow regimes (Achour et al., 2022a; 2022b; 2022c). The precise flow measurement capability of the modified H-Flume contributes to improved analysis and prediction of local scour phenomena around hydraulic structures by providing accurate discharge data has given by Achour et al. (2025). In alluvial stream continuous transportation of sediment can be seen as a geomorphologic process. If something disrupts this sediment transportation process by constructing barrages, dams etc, it may cause a long-term change in the stream bed evaluation (Beg, 2013). On the other hand, scouring and dam siltation are intrinsically linked through the redistribution of sediment within river systems, where excessive upstream erosion can accelerate reservoir sedimentation and reduce storage capacity (Remini and Remini, 2003; Remini, 2010; Remini and Bensafia, 2016: Remini, 2017; Remini et al., 2019). Due to the continuous sediment transportation if it deposits in the reach length and due to the deposition if river bed increases then it is called aggradations and in an opposite way, due to the erosion if sediment bed decreased day by day, then it is called degradation. But in total scour aggradations does not have any contribution as per Smith (1994). Lacey's regime formula is developed in 1930 which was based on limited field data from Punjab, with rate of flow values ranging from 0.70 to 173 $m^3/s$. Majumder et al. (2006) applied this concept to the Ganga River. Their study showed that reducing the waterway width from 3.6 km to 2 km increased abutment scour by 1.6 times and contraction scour by 3.9 times. This highlights the important role of waterway width in bridge foundation design. Additionally, Tiwari et al. (2012) found that changing the angle of attack by just 5° resulted in a 10% change in pier scour depth. The separation of the upstream incoming boundary layer and formation near the bottom of necklace like vertical structures are commonly known as horseshoe vortices, which stretch around the pier and fold around its upstream. According to Lu et al. (2011), turbulence in the upstream flow causes continuous changes in the location, size, and intensity of the vortices over time.

Extensive research has been conducted on local scour around single bridge piers and abutments, with detailed analysis of flow characteristics, sediment transport, and the role of hydraulic structures (Dey et al., 1995; Ghorbani, 2008; Achour et al., 2024; Ghasemi Asl and Heidarnajed, 2023; Dala and Deb, 2024; Bagheri et al., 2024). Most existing studies focus on isolated structures or generalized hydraulic conditions, without accounting for the complex flow interactions, altered turbulence patterns, and cumulative effects of multiple closely spaced bridge piers found in parallel bridges. The impact of flow interference between these parallel structures on scour depth, vortex formation, and sediment transport remains underexplored.

HEC-RAS (Hydrologic Engineering Center's River Analysis System) has emerged as an indispensable computational tool for engineers and hydrologists, offering robust capabilities in modeling open-channel flow, which is fundamental for accurate flood forecasting and risk assessment (Ben Said et al., 2024; Athmani et al., 2025; Ezz, 2025). In flood risk management and mapping (Bekhira et al., 2019), HEC-RAS allows for the detailed mapping of floodplains and the identification of high-risk zones, supporting decision-makers in the development of effective mitigation strategies (Aroua, 2020), urban planning, and emergency response protocols (Boulghobra, 2013; Nezzal et al., 2015; Ayari et al., 2016; Benslimane et al., 2020).

Beyond flood modeling, HEC-RAS plays a vital role in the design and optimization of hydraulic structures such as culverts, bridges, spillways, and levees, by simulating flow interactions with infrastructure under varying boundary and channel conditions. HEC-RAS plays a pivotal role in addressing local scour problems around hydraulic structures by accurately simulating flow patterns, velocity distributions, and shear stresses, key parameters that govern the initiation and development of scour under varying hydraulic and geomorphological conditions. Despite substantial research on local scour around single bridge piers and abutments, there is a lack of understanding of local scour dynamics in parallel bridge configurations, where flow interference, altered turbulence patterns, and cumulative hydraulic effects between closely spaced piers are not adequately studied. Furthermore, current modeling tools like HEC-RAS are often calibrated for single bridge systems, potentially limiting their accuracy in simulating the compounded hydraulic effects present in parallel bridge scenarios. Therefore, further investigation is needed to quantify and predict the variation of local scour at parallel bridges under varying hydraulic and geometric conditions.

## STUDY AREA

The study area is located near Golaghati in Tripura over Burima River. The latitude and longitude of Golaghati Bridge are 23° 68' N and 91° 36' E respectively. The Golaghati Bridge in Bishalgarh, Tripura is a critical structure for studying scour depth around bridge piers due to its location in a flood-prone, alluvial region. Scour analysis is essential to ensure its structural safety and durability. The study area significantly enhances regional connectivity, boosts economic growth through trade and tourism, and improves disaster response during floods. Additionally, this bridge supports sustainable development, environmental protection, and regional stability. Thus, evaluating local scour is vital not only from an engineering perspective but also for broader socio-economic and strategic reasons. Image 1 shows the pictorial representation of the Golaghati bridge.

**Image 1: Pictorial representation of the Golaghati bridge**

The Burima Bridge, located over the Burima River, is designed for a peak discharge of 335 $m^3/s$. The bridge comprises four spans of 16.0 meters each, with a total length of 65.0 meters. It has an overall structural width of 9.0 meters, including a 7.0-meter-wide carriageway. The formation level is set at 101.356 meters, with the high flood level (HFL) recorded at 99.500 meters and the lowest riverbed level at 96.120 meters. The average flow velocity at the site is 1.739 m/s. The substructure includes pile foundations with a length of 22 meters, while the piers have a uniform width of 1 meter. These structural and hydraulic parameters form the basis for assessing the bridge's hydraulic performance and scour potential.

## DATA COLLECTION

Thirty year's peak discharge data for Burima River is collected from Water Resource Division, Bisalgarh. These data include section of the bridge at various intervals, HFL, LBL, water depth etc. The graphical representation of the data is shown in Fig. 1. It is shown that the maximum peak discharge over thirty years was occurred during the year 1980 to 2010. In the present study scouring due to flood has been computed.

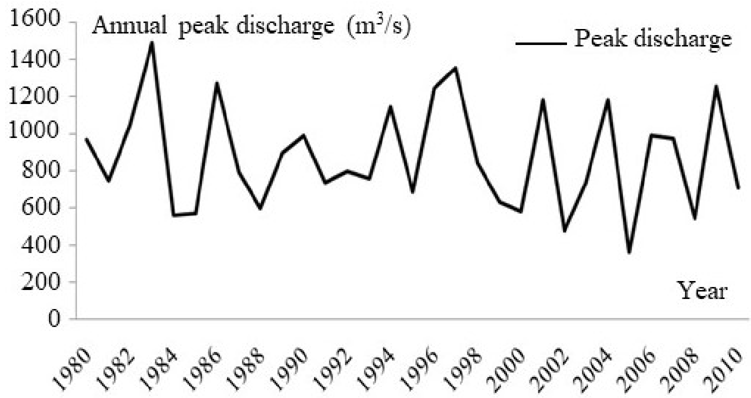



**Figure 1: Peak discharge data of Burima River for the period 1980 - 2010**

Using an auger, soil samples were collected from the bridge site. A grain size distribution curve is prepared with the soil sample of Burima River. The results are illustrated in Fig. 2. The $d_{50}$, representing the particle size for which 50% of the sample, by weight or volume, is finer and 50% is coarser. value was found from this analysis and subsequently utilized for scour evaluation using the HEC-RAS modeling tool (Setia, 1997).

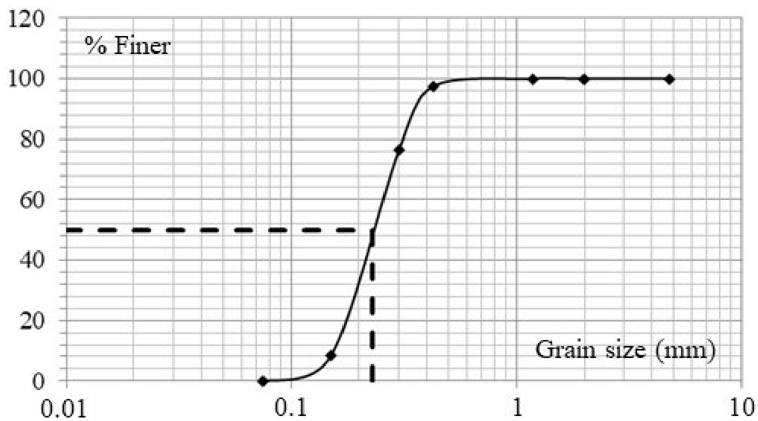



**Figure 2: Grain size distribution curve of Burima River**

**METHODOLOGY**

Numerous empirical equations have been developed to predict scour depth around bridge piers. Among these, the Colorado State University (CSU) equation is widely recognized and utilized for estimating the maximum depth of scour around the piers which is applicable to both live-bed and clear-water conditions. The CSU equation is formulated as follows (Richardson and Davis, 1995):

$$y_s = 2k_1k_2k_3k_4a^{0.65}y_1^{0.35}F_{r1}^{0.43} \tag{1}$$

where, $y_s$ = Maximum scour depth (m); $Fr_1$ = Approach Froude Number; $a$ = Width of bridge pier (m); $K_1$ = Factor for nose shape of pier; $K_2$ = Factor for angle of attack; $K_3$ = Factor for condition of bed; $K_4$ = Factor for armoring of bed material; $y_1$ = Flow depth directly upstream of the pier (m).

The HEC-RAS software now includes a local pier scour equation proposed by Dr David Froehlich (Froehlich, 2013) as an alternative to the widely used CSU equation. This equation is formulated as follows:

$$y_s = 0.32\varphi a^{0.62}y_1^{0.47}F_{r1}^{0.22}d_{50}^{-0.09} + a \tag{2}$$

where, $\varphi$ = Factor for nose shape of pier; $a$ = Width of the pier, $d_{50}$ = Median grain size of the bed material (mm).

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

**Development of scour model using HEC-RAS**

The HEC-RAS software has proven to be a reliable tool for predicting local scour and mobile bed conditions in riverine environments (Gibson et al., 2006). Recent research has further demonstrated its effectiveness in complex hydraulic conditions, including parallel bridge configurations (Mehta and Yadav, 2020), and in experimental investigations of scour countermeasures such as roughening elements on abutments. In this study, a pier scour model for the Golaghati Bridge over the Burima River was developed using HEC-RAS version 5.0.3. The model was evaluated under two hydraulic scenarios: a full waterway condition representing unobstructed flow, and a 30% restricted waterway condition simulating flow obstruction due to debris or structural encroachment. Essential hydraulic and hydrological data, including bed slope, channel cross-sections, Manning's roughness coefficients, and peak discharges for return periods of 475, 711, 1147, and 1495 m³/s, were incorporated. Bridge geometry, including deck elevation, pier dimensions and spacing, and alignment, was input using the HEC-RAS bridge geometry editor. The steady flow analysis accounted for subcritical, supercritical, and mixed flow regimes. Model calibration and validation were conducted using observed water surface profiles, with adjustments to Manning's *n* values and slope configurations to enhance accuracy. The scour analysis involved several systematic steps: defining cross-sections with elevation and roughness data; activating the bridge scour module; inputting sediment size ($d_{50}$); selecting circular pier shapes; positioning a new bridge at various upstream and downstream locations relative to the existing structure; and executing steady flow simulations. The influence of bridge positioning, whether upstream or downstream, on hydraulic behavior has critical implications for scour mitigation. Advanced data-driven and AI-based models, including machine learning and neuro-fuzzy systems, are increasingly being explored to enhance flood prediction and flow estimation (Kedam et al., 2024; Kantharia et al., 2024). These approaches offer promising complementary tools for analyzing complex hydraulic interactions in bridge design. The results provide valuable insights into the influence of hydraulic conditions and bridge geometry on local scour development, supporting safer and more resilient bridge design, effective maintenance planning, and comprehensive flood risk management at the Golaghati Bridge site.

## Model Calibration

In this study, the scour depth computed using the hydraulic modeling tool is compared with several empirical scour equations developed by various researchers, as documented by Mueller et al. (1994). The following are the equations considered for comparison

### *Ahmad equation*

The Ahmad equation (1953) (Eq. 3) accounts for the flow depth at the bridge pier as a function of discharge per unit width and a coefficient related to boundary geometry and pier characteristics. This is a well-known citation in hydraulic engineering literature where Ahmad's equation is often used in the context of local scour and flow behavior near hydraulic structures. It reads as follows:

$$y_{sp} = Kq^{2/3} - y_0 \tag{3}$$

where $y_{sp}$ = Flow depth at the bridge pier, including local pier Scour; $y_0$ = Flow depth just upstream from the bridge pier or abutment, excluding local scour; $q$ = discharge per unit width; $K$ = a coefficient that is a function of boundary geometry, abutment shape, width of the piers, shape of the piers, and the angle of the approach flow.

### *Blench–Inglis equation*

The Blench–Inglis equation (1949) (Eq. 4) estimates scour depth based on flow depth, velocity, and discharge per unit width upstream from the pier. Their research contributed to understanding the relationship between channel conditions and scour processes around bridge piers. It reads as follows:

$$y_{sp} = 1.8\, y^{0.25} q^{0.5} \left( \frac{y_0}{V_0^2} \right)^{0.25} - y_0 \tag{4}$$

where $V_o$ = velocity of water at bridge pier or abutment. All the other parameters in Eq. (4) have already been defined earlier.

***Colorado State University equation***

The Colorado State University equation (Richardson and Davis, 2001) (Eq. 5) incorporates shape and angle correction factors along with the Froude number to evaluate scour depth. This equation can be written as follows:

$$y_{sp} = 2\,y_0 k_1 k_2 \left(\frac{b}{y_0}\right)^{0.65} F_{r1}^{0.43} \tag{5}$$

This reference provides the theoretical basis and empirical formulation of the equation as developed and used by Colorado State University researchers, particularly in the context of bridge pier scour. In the context of the Colorado State University equation, the parameter *b* typically represents the Pier width, measured normal to the flow direction. The Froude number $F_r$ refers specifically to the approach flow Froude number, evaluated just upstream of the pier or obstruction. All the other parameters in Eq. (5) have already been defined earlier. The difference between Eq. (1) and Eq. (5) is purely notational, not structural. It is likely that "*b*" represents pier width, just as "*a*" does in the original CSU formula.

***Froehlich equation***

The Froehlich equation (1988) (Eq. 6) uses pier geometry, upstream flow depth, grain size, and approach flow characteristics. This equation can be written as follows:

$$y_{sp} = 0.32\,b\,\varphi \left(\frac{b^*}{b}\right)^{0.62} \left(\frac{y_0}{b}\right)^{0.46} F_{r0}^{0.2} \left(\frac{b}{d_{50}}\right)^{0.08} \tag{6}$$

where $b^*$ = Pier thickness projected normal to the approach flow; $F_{r0}$ = Froude number of the approaching flow. All the other parameters in Eq. (6) have already been defined earlier.

***Inglis–Poona equation***

The Inglis–Poona equation (1949) (Eq. 7) relates scour depth to the ratio of upstream depth to pier thickness. It reads as follows:

$$y_{sp} = 1.73\,b \left(\frac{y_0}{b}\right)^{0.78} - y_0 \tag{7}$$

All the parameters in Eq. (7) have already been defined earlier.

The Inglis–Poona equation is an empirical relationship developed to estimate scour depth around bridge piers and abutments. It is based on experimental and field observations. In addition, this equation is particularly relevant for preliminary design assessments in river hydraulics and provides a simple method to estimate local scour when detailed hydrodynamic modeling is not feasible. It assumes clear-water scour conditions and uniform flow approach.

Furthermore, the term "Inglis–Poona equation" is a shorthand or conventional designation, not a standard author citation. The name "Poona" refers to the Poona Research Station (now Pune), where the empirical studies and experimental research leading to this equation were conducted. So, "Poona" is not a co-author, but the research station/location that contributed institutional context and credibility. The term "Inglis–Poona" became common in Indian hydraulic literature to acknowledge both the author and the place of origin of the research.

***Larras equation***

The Larras equation (1963) (Eq. 8) estimates scour based on a shape factor and pier dimensions. It reads as follows:

$$y_{sp} = 1.42 K_{s2} b^{0.75} \tag{8}$$

where, $b$ is the pier thickness, or the effective width of the pier obstructing flow. It plays a direct role in how flow separates and vortices are generated, leading to scour. $K_{S2}$ = Factor for nose shape, also called a shape factor. It accounts for the influence of the nose shape of the pier; for circular noses, $K = 1.5$; for rectangular noses, $K \approx 2$; for sharp noses or more streamlined shapes, $K = 1$ or less.

Furthermore, this equation is simple and widely used in preliminary bridge design studies, especially in France and francophone hydraulic engineering communities. Its empirical nature makes it easy to apply, but for detailed safety or design studies, it should be complemented with more comprehensive models or physical testing.

***Shen–Maza equation***

The Shen - Maza equation (1964) is used for estimating the local scour depth around bridge piers caused by flowing water. It expresses the scour depth as a function of hydraulic conditions represented by the pier Froude number, which incorporates both the approach flow velocity, and the flow depth just upstream of the pier. This equation is particularly useful in the preliminary design and safety assessment of bridge foundations against scour-induced failure.

The Shen–Maza equation expresses scour depth directly as a function of the pier Froude number, as follows:

$$y_{sp} = K F_p^{n} \tag{9}$$

where, $F_p$ = Pier Froude Number, which must be calculed using the approach velocity.

*K*, *n* = empirical coefficients derived from experimental data; *K* captures the intensity of local scour, and *n* indicates the non-linear relationship between the pier Froude number and relative scour depth. The exact coefficients *K* and *n* depend on pier shape, sediment properties, and flow conditions and are provided in the original paper by Shen and Maza (1964).

For cylindrical piers in uniform non-cohesive sediments under clear-water scour conditions, the empirical coefficients *K* and *n* take the values *K* = 3.4, and *n* = 0.67. These values are based on experimental observations and represent typical scour conditions under controlled laboratory environments. In field applications, adjustments may be necessary to account for pier shape, sediment gradation, flow obliquity, debris accumulation, or other complexities. Thus, Shen-Maza equation, specifically applicable to cylindrical (circular) piers embedded in uniform, non-cohesive sediments and subjected to clear-water scour conditions, is reduced to the following:

$$y_{sp} = 3.4\, F_p^{0.67} \tag{10}$$

## Model validation

To ensure the accuracy and reliability of the developed HEC-RAS scour model for the Golaghati Bridge, a statistical validation was performed using correlation analysis. Correlation serves as a quantitative measure to evaluate the strength and direction of a linear relationship between observed and simulated scour values. In this study, the simulated scour depths generated by HEC-RAS were compared against results from widely recognized empirical equations, including CSU, Larras, Ahmed, Blench-Inglis, Shen-Maza, Inglis-Poona, and Froehlich models. The analysis employed parametric methods such as linear regression and ordinary least squares (OLS) regression to assess the degree of agreement. The resulting correlation coefficients demonstrate a strong positive relationship between the HEC-RAS model outputs and the empirical equations.

# RESULTS AND DISCUSSION

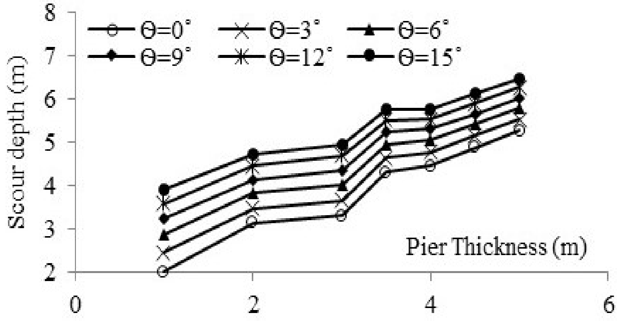
## Estimation of scour depth

Scour depends on many factors like the velocity of flow, discharge, water depth, angle of attack, pier diameter, sediment size, and pier shape (Elsebaie, 2013). This study is considering only discharge, diameter of pier and angle of attack as variable. Angle of attack varies from 0° to 15° and pier diameter varies from 1m to 5m. Scour profile is examined for both the conditions. One is full stretch water way and another is 30 percent restricted water way. Table 1 shows all the value of scour which is generated in HEC-RAS modeling tool for both conditions.

From the above Table 1, it is clear that the scour in river bed increases with the increase of diameter of pier and angle of attack. The graphical representation between diameter of pier and scour depth with angle of attack for Golaghati Bridge is given in Fig.4

**Table 1: Scour Depth Variation at Golaghati Bridge**

| **Types of Flow** | **Angle of Attack (Degree)** | **Thickness of pier (m)** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 3.5 | 4 | 4.5 | 5 |
| | | Local scour around bridge pier (m) | | | | | | |
| Full Stretch 65 m | 0 | 2.02 | 3.31 | 4.31 | 4.47 | 4.88 | 5.27 | 5.42 |
| | 3 | 2.47 | 3.67 | 4.65 | 4.78 | 5.17 | 5.53 | 6.92 |
| | 6 | 2.89 | 4.04 | 4.95 | 5.05 | 5.42 | 5.80 | 6.15 |
| | 9 | 3.26 | 4.37 | 5.25 | 5.32 | 5.66 | 6.01 | 6.38 |
| | 12 | 3.60 | 4.70 | 5.51 | 5.54 | 5.91 | 6.27 | 6.60 |
| | 15 | 3.92 | 4.97 | 5.77 | 5.76 | 6.15 | 6.48 | 6.77 |
| Contraction Scour | | 0.59 | 0.59 | 0.59 | 0.59 | 0.59 | 0.59 | 0.59 |
| Effective Flow 3.55m | 0 | 2.41 | 3.69 | 4.80 | 5.23 | 5.63 | 4.55 | 4.82 |
| | 3 | 2.73 | 4.09 | 5.18 | 5.20 | 5.97 | 4.77 | 5.07 |
| | 6 | 3.10 | 4.50 | 5.52 | 5.91 | 6.25 | 5.00 | 5.26 |
| | 9 | 3.4 | 4.87 | 5.85 | 6.23 | 6.53 | 5.18 | 5.45 |
| | 12 | 3.8 | 5.24 | 6.14 | 6.49 | 6.81 | 5.41 | 5.64 |
| | 15 | 4.2 | 5.53 | 6.43 | 6.75 | 7.09 | 5.59 | 5.79 |
| Contraction Scour | | 2.08 | 2.24 | 2.46 | 2.73 | 3.06 | 3.90 | -- |



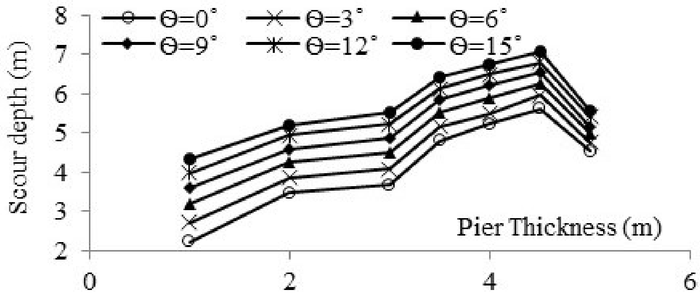



**Figure 3: Scour depth variation uder two flow conditions: (a) Full Waterway and (b) Restricted Waterway. Θ = Angle of Attack**

**Calibration of scour depth**

Several others hydraulic models are there for scour prediction. Now a day's HEC-RAS is using all worldwide to find the scour depth. It is more acceptable than the other models (Khassaf et al., 2013). There is a scope of comparing scour depth computed by HEC-RAS tool with other scour models (Haghiabi et al., 2012). Fig. 4 presents a comparative analysis of scour depth predictions from seven empirical models against the reference results obtained from HEC-RAS simulations. The chart visually differentiates between models that either underestimate or overestimate scour depth relative to the HEC-RAS output, which serves as the benchmark for this study. The vertical axis represents scour depth (in meters), while the horizontal axis lists the respective scour prediction models: Ahmad, Blench-Inglis, CSU, Froehlich, Inglis-Poona, Larras, and Shen-Maza. Bars extending below the zero line indicate models that underpredict scour depth, while those above the line represent overprediction. The Shen-Maza model significantly underestimates scour depth, followed by the Inglis-Poona and Blench-Inglis models, indicating a conservative prediction of local scour. The Ahmad and CSU models also predict lower scour depths but with less deviation. In contrast, the Froehlich and Larras models slightly overestimate the scour depth.

Regarding the model behavior across the spectrum, Fig. 4 not only distinguishes between under- and overestimation but also implicitly highlights the conservativeness or aggressiveness of each empirical model. For example: Froehlich and Blench-Inglis are conservative, potentially suitable for preliminary safety-focused designs, especially in sediment-sensitive regions; Larras and Shen-Maza, which overpredict scour, may offer upper-bound estimates for use in worst-case scenario assessments.

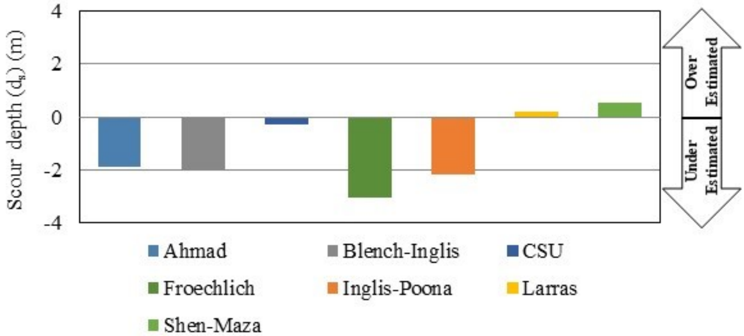



**Figure 4: Overestimated and Underestimated Scour Predictions in Comparison to the HEC-RAS Model**

Concerning the sensitivity to input parameters, the deviation trends suggest each model's sensitivity to variables such as pier diameter, flow velocity, and sediment size. Models with constant or low variation, like Ahmad's, may not adequately capture these dynamics, while those with steeper bars, such as Shen-Maza, react more sharply to them.

As for implication for design practices, the Fig. 4 helps practitioners identify risk trade-offs, whether to adopt a model that slightly overpredicts (erring on the side of caution) or one closely matching HEC-RAS (e.g., CSU), which balances realism and economy.

As visual benchmarking aid, Fig. 4 could be interpreted as a quick visual guide for model selection. Models close to the zero line, e.g., CSU, and Larras, show good agreement with HEC-RAS and might be favored when detailed modeling is not feasible. This adds a practical dimension to the Figure's utility beyond mere comparison.

In addition to indicating over- and underestimation trends, Fig. 4 enables a practical clustering of empirical models based on their predictive alignment with the HEC-RAS benchmark. The models can be grouped as follows: Group A (Close to HEC-RAS) includes the CSU and Larras equations, both of which demonstrate high fidelity and minimal deviation, making them suitable for detailed design applications; Group B (Moderate Underestimators) comprises the Ahmad, Blench–Inglis, and Inglis-Poona models, which consistently predict lower scour depths and may be useful for preliminary or conservative assessments; Group C (Outliers) includes the Froehlich model, which significantly underestimates, and the Shen-Maza model, which overestimates scour depth. This categorization facilitates more informed model selection, allowing engineers to balance reliability against safety-oriented conservatism depending on the design objectives and available data.

In addition to highlighting model deviation, Fig. 4 also allows for categorization of the empirical equations based on their predictive tendencies. CSU and Larras models emerge as the most reliable approximators of HEC-RAS predictions, supporting their broader acceptance in engineering practice. Meanwhile, conservative models like Froehlich or Inglis–Poona may be cautiously preferred in preliminary design stages where overestimation is desirable. The visualization also implies each model's sensitivity to hydraulic variables and serves as a practical benchmark for model selection under varying data availability or project constraints."

**Comparison of Empirical Models with HEC-RAS Predictions**

Table 2 aims to compare the predicted scour depths around bridge piers of different diameters using various empirical scour equations with the results obtained from the HEC-RAS model. The purpose is to assess the accuracy, consistency, and conservatism of empirical approaches relative to a physically based hydraulic simulation. The column labeled "Present study" refers to the simulated results obtained using the HEC-RAS model developed and calibrated as part of the current research.

**Table 2: Comparison of scour depth variation at Golaghati Bridge using HEC-RAS and Empirical models**

| **Model** | **Pier diameter (m)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1.00 | 2.00 | 3.00 | 3.50 | 4.00 | 4.50 | 5.00 |
| | Variation of scour depth (m) | | | | | | |
| Ahmad | 2.41 | 2.41 | 2.41 | 2.41 | 2.41 | 2.41 | 2.41 |
| Blench-Inglis | 1.27 | 2.05 | 2.57 | 2.78 | 2.98 | 3.15 | 3.31 |
| CSU | 1.98 | 3.10 | 4.03 | 4.46 | 4.86 | 5.25 | 5.62 |
| Froechlich | 0.65 | 1.01 | 1.29 | 1.42 | 1.55 | 1.66 | 1.77 |
| Inglis-Poona | 1.08 | 1.72 | 2.15 | 2.32 | 2.48 | 2.62 | 2.74 |
| Larras | 1.99 | 3.34 | 4.53 | 5.09 | 5.62 | 6.14 | 6.65 |
| Shen-Maza | 1.62 | 3.25 | 4.87 | 5.68 | 6.49 | 7.31 | 8.12 |
| Present study | 2.15 | 3.31 | 4.31 | 4.47 | 4.88 | 5.27 | 5.42 |

Table 2 highlights the following key aspects: Ahmad's Equation predicts a constant scour depth of 2.41 m regardless of pier diameter. This suggests oversimplification, as it does not account for pier geometry; Blench–Inglis and Inglis–Poona equations show increasing scour depth with pier diameter, but their estimates remain significantly lower than HEC-RAS, indicating conservative predictions; CSU Equation aligns relatively well with HEC-RAS values, especially for intermediate diameters, reflecting its widespread acceptance and adaptability in practice; Froehlich's Equation tends to underpredict scour depth for all pier sizes, possibly due to limitations in accounting for complex flow conditions or sediment variability; Larras and Shen–Maza Equations overpredict scour depth as pier diameter increases, suggesting higher sensitivity to geometric and hydraulic parameters; Larras and Shen–Maza models closely follow the trend shown by HEC-RAS but with greater magnitude; The HEC-RAS results serve as a benchmark and lie between the extremes of underestimation (e.g., Froehlich) and overestimation (e.g., Shen–Maza), providing balanced and data-driven predictions.

The sensitivity of each model to pier diameter varies significantly. Empirical equations need calibration or caution when used for bridges in complex configurations, such as parallel pier arrangements.

Table 2 underscores the importance of using complementary modeling tools and justifies the application of HEC-RAS as a robust tool for scour assessment, especially when **site-**specific data and complex pier arrangements are involved.

**Influence of the upstream adjacent bridge on the hydraulic behavior at Golaghati Bridge**

This section investigates the presence of a proposed upstream bridge influences the hydraulic behavior and local scour characteristics at the existing Golaghati Bridge. The study considers three configurations, where the new bridge is located at distances of 4 m (Phase-I), 100 m (Phase-II), and 140 m (Phase-III) upstream from the existing bridge. To evaluate these effects, historical flood discharges of 1495 cumecs (1983), 1147 cumecs (1989), 711 cumecs (2010), and 475 cumecs (2002) were analyzed. The corresponding scour depths and Froude numbers are summarized in Table 3.

**Table 3: Variation in Froude's number with scour depth on existing bridge**

| Sl. No. | Scour Depth(m) | Froude's Number | Flow ($m^3/s$) |
|---|---|---|---|
| 1 | 3.27 | 0.23 | 475 |
| 2 | 4.83 | 0.29 | 711 |
| 3 | 6.68 | 0.34 | 1147 |
| 4 | 6.75 | 0.33 | 1495 |

The results show that the presence of an upstream bridge significantly alters the approaching flow characteristics. Specifically, the additional structure increases overall flow resistance upstream, thereby reducing the approach velocity at the Golaghati Bridge. This leads to a decrease in the Froude number, indicating subcritical flow conditions and a less energetic flow regime at the location of the existing pier.

From a physical standpoint, the upstream bridge acts as a flow retarder, dissipating part of the incoming flow's energy through increased turbulence, eddy formation, and wake zone development behind its piers. This reduction in energy and momentum translates into a lower shear stress exerted on the bed materials around the existing bridge piers, thereby reducing local scour depth. Furthermore, the upstream structure effectively shields the downstream bridge from the full force of the approaching flow, especially when the spacing is relatively small (e.g., 4 m). This shielding effect diminishes with increasing distance, yet still plays a role at 100 m and 140 m.

Overall, the presence of an upstream bridge in parallel configuration leads to reduced hydraulic intensity at the downstream bridge, improving its stability by decreasing both the Froude number and scour depth. The findings, presented in Table 4, underscore the importance of considering flow interference and energy redistribution when designing adjacent bridge structures.

**Table 4: Changes in scour depth and Froude's number at an existing bridge when another bridge is built 4m, 100m, and 140m upstream**

| Sl. No. | Flow ($m^3/s$) | 4 m upstream | | 100 m upstream | | 140 m upstream | |
|---|---|---|---|---|---|---|---|
| | | Scour depth | Froude's Number | Scour depth | Froude's Number | Scour depth | Froude's Number |
| 1 | 475 | Reduced | Reduced | Reduced | Reduced | Reduced | Reduced |
| 2 | 711 | Reduced | Reduced | Reduced | Reduced | Reduced | Reduced |
| 3 | 1147 | Reduced | Reduced | Reduced | Reduced | Reduced | Reduced |
| 4 | 1495 | Reduced | Reduced | Reduced | Reduced | Reduced | Reduced |

**Influence of the downstream adjacent bridge on the hydraulic behavior at Golaghati Bridge**

This section evaluates the impact on the current bridge when a new bridge is proposed downstream and adjacent to it. Three distinct cases were analyzed: Case-I, where the proposed bridge is located 4 m downstream of the Golaghati Bridge; Case-II, where it is located 100 m downstream; and Case-III, where it is situated 140 m downstream. To assess the scour depth at the existing bridge, the influence of the neighboring bridge was examined for flood events with discharges of 1495 cumecs (1983), 1147 cumecs (1989), 711 cumecs (2010), and 475 cumecs (2002).

Table 5 presents a comparative analysis between the single-bridge and dual-bridge scenarios, highlighting that the presence of a downstream bridge can intensify local scour. This is primarily due to hydraulic constriction and the resultant increase in energy concentration within the vicinity of the upstream bridge pier.

**Table 5: Changes in scour depth and Froude's number at an existing bridge when another bridge is built 4m, 100m, and 140m downstream**

| Sl. No. | Flow ($m^3/s$) | 4 m downstream | | 100 m downstream | | 140 m downstream | |
|---|---|---|---|---|---|---|---|
| | | Scour depth | Froude's Number | Scour depth | Froude's Number | Scour depth | Froude's Number |
| 1 | 475 | Increased | Increased | Increased | Increased | Increased | Increased |
| 2 | 711 | Increased | Increased | Increased | Increased | Increased | Increased |
| 3 | 1147 | Increased | Increased | Increased | Increased | Increased | Increased |
| 4 | 1495 | Decreased | Decreased | Increased | Decreased | Increased | Decreased |

The presence of a downstream bridge tends to increase the local scour depth at the existing bridge for lower discharge events (475, 711, and 1147 cumecs), as well as the associated Froude number. This is primarily due to the constriction and backwater effect induced by the downstream structure, which alters the normal outflow patterns from the existing bridge.

Physically, the downstream bridge acts as a flow bottleneck, creating a zone of elevated water surface elevation between the two bridges. This leads to increased flow acceleration and turbulence around the piers of the upstream (existing) bridge. The contraction of the flow between the two bridges especially in the 4 m spacing configuration enhances local shear forces on the riverbed, resulting in higher scour depths. Additionally, the presence of the downstream pier can reflect turbulent eddies upstream, compounding the unsteady flow characteristics and contributing to intensified bed degradation.

Notably, during the highest discharge event of 1495 cumecs, a decrease in the Froude number was observed, which is likely attributable to a temporary backwater effect that altered the flow regime. Despite this reduction in Froude number, the scour depth at the existing bridge increased. This phenomenon suggests that the combined influence of elevated flow velocity and modified pressure gradients intensifies the vertical flow components around the bridge pier, thereby exacerbating local scour. These findings underscore the critical importance of understanding the complex interactions between flow dynamics and structural elements in multi-bridge configurations.

**Discharge - Scour relationship and hydraulic vulnerability analysis**

Fig. 5 graphically presents the relationship between scour depth, denoted (*d*s) herein, and discharge ($Q$) at the Golaghati Bridge.
The rate of flow data was entered into HEC-RAS to compute the associated scour depths, thereby illustrating the changes in depth of scour with respect to discharge. The resulting relationship, illustrated in Fig. 5, highlights a positive non-linear correlation between discharge $Q$ and scour depth *d*s, suggesting that as the river discharge increases, the resulting local scour depth also increases at an accelerating rate. This trend is consistent with hydraulic theory, as greater discharges lead to higher flow velocities and shear stresses, which in turn intensify sediment entrainment and scouring around bridge piers.

This relationship provides critical insights into the hydraulic vulnerability of the bridge under varying flood conditions.

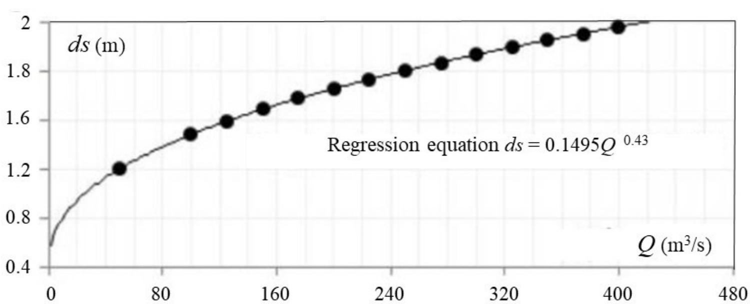



**Figure 5: Changes in depth of scour with respect to discharge at the Golaghati Bridge**

Notably, the curve in Fig. 5 indicates that even moderate increases in discharge result in disproportionately larger increases in scour depth. This behavior highlights the vulnerability of bridge foundations during extreme hydrologic events.

The shape of the curve in Fig. 5 may also reflect the transition between subcritical and supercritical flow regimes, where turbulence and flow separation intensify near pier structures, thereby deepening scour holes. These insights are particularly important for bridge design codes and risk assessment, suggesting that fixed safety margins based on linear discharge-scour relationships may be inadequate.

Given the observed non-linear relationship between discharge and scour depth, it becomes evident that traditional linear scaling in design margins may not provide adequate protection during high-flow events. Therefore, a non-linear increase in conservatism, proportional to the anticipated peak discharges, should be integrated into hydraulic design criteria, especially for critical infrastructure such as bridge foundations and abutments.

The intensification of scour under extreme hydraulic conditions necessitates that protective structures be designed with reference to maximum credible flood events, rather than mean or median flow rates. Elements like riprap layers, pier collars, and guide banks must therefore be scaled to withstand intensified erosive forces associated with turbulent, high-velocity flows that typically accompany supercritical transitions.

The capacity of the HEC-RAS model to replicate the observed non-linear scour response demonstrates its relevance as a decision-support tool for modern hydraulic engineering. As climate variability increases the frequency and intensity of extreme weather events, reliance on robust modeling tools like HEC-RAS is critical for anticipating vulnerabilities and developing adaptive, resilient infrastructure strategies.

**Parametric influence and dimensionless analysis of scour depth**

Figs. 7 through 10 present the outcomes of a nondimensional analysis conducted to understand how key hydraulic and geometric parameters influence the depth of local scour around bridge piers. This type of analysis supports generalization of results and provides insights into the behavior of scour under varying, but dimensionless, flow and structural conditions.

The nondimensional analysis technique is performed to get the variables affecting the depth of scour near the piers in dimensionless groups. The HEC-RAS model data is utilized to illustrate the relationship between these dimensionless parameters and local scour.

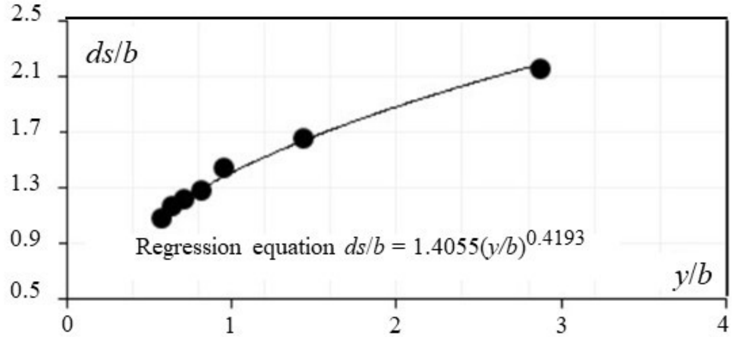



**Figure 6: Variation of scour with flow depth in Burima River**

Fig. 6 aims to assess how local scour depth (normalized by pier diameter) varies with flow depth (also normalized). A clear increasing trend indicates that as the upstream flow depth increases, the depth of scour becomes more significant relative to pier diameter. This supports the understanding that deeper flows provide greater potential energy and flow momentum, which intensify sediment removal near piers.

Fig. 7 aims to relate the scour depth to the Froude number ($F_r$), a dimensionless parameter representing flow regime. Scour depends on many factors; one is the flow depth. All the variables are makes to dimensionless by dividing with the pier diameter (Dey et al., 1995). Data from the hypothetical model showed that flow velocity has a direct effect on depth of scour. The effect of the flow velocity is considered by studying the effect of pier's Froude number with depth of scour (Ahmad et al., 2024). Fig. 7 shows this variation. In addition, the plot reveals a strong positive relationship, confirming that **as** flow becomes more energetic (higher $F_r$), the potential for scouring increases. This aligns with physical expectations, greater velocity and momentum lead to more vigorous vortex formation and sediment entrainment near the pier.

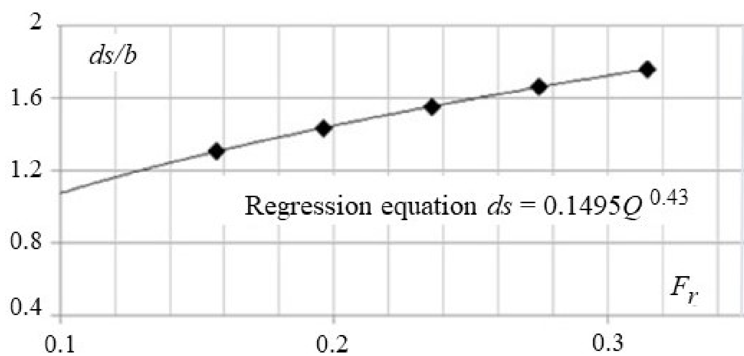



**Figure 7: Changes in depth of scour with Froude Number in the Burima River**

Fig. 8 intends to analyze the effect of flow obliquity (angle of attack) on scour development. The angle of attack significantly influences the depth of scour. Fig. 8 shows that with increasing the pier inclination from 0° to 15° results in a 54.02% increase in local scour depth. This demonstrates how even small flow deflections can destabilize sediment near the pier due to asymmetric vortex development and skewed flow separation.

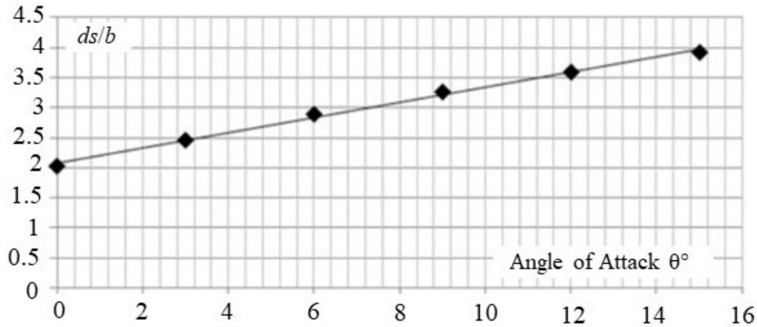



**Figure 8: Changes in dpeth of scour to angle of attack in the Burima River**

Fig. 9 helps to understand the impact of pier number and shape, encapsulated in the contraction ratio. It shows that the contraction ratio strongly influences scour depth, more or bulkier piers reduce the effective flow width, accelerating water through narrower passages. This increased velocity intensifies local scour, especially around the centerline and sides of the piers.

Pier shape and quantity have a notable impact on local scour depth. The number of piers is represented through the contraction ratio, defined as the sum of the openings between piers divided by the total channel width. Fig. 9 illustrates the influence of both pier shape and number on the depth of scour.

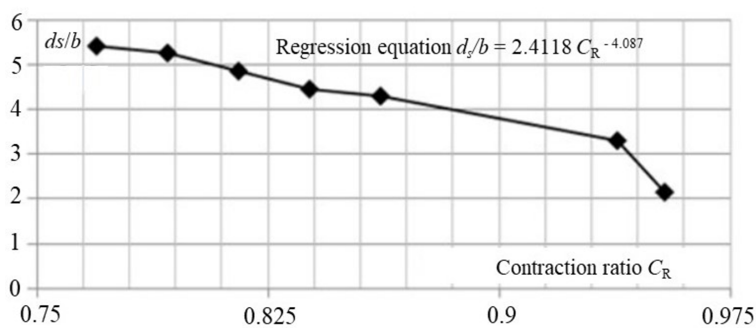



**Figure 9: Changes in depth of scour to contraction ratio in the Burima River**

As general comments, the nondimensional analysis presented through Figs. 7 to 10 offers several critical insights into the interplay between hydraulic parameters and structural configurations affecting local scour. These findings have meaningful implications for both design and modeling.

First, the results confirm that scour depth is *non-linearly sensitive* to both flow conditions (such as Froude number and upstream flow depth) and structural characteristics (such as pier shape, number, and angle of attack). This non-linearity highlights the importance of considering extreme hydraulic events, rather than average or steady-state flows, when designing scour protection measures around bridge piers.

Second, the ability of the HEC-RAS model to capture these complex, dimensionless relationships support its effectiveness as a reliable tool for simulating local scour processes in compound bridge geometries. The model's outputs align well with physical expectations and observed trends, reinforcing its applicability in both research and practice.

Third, the figures illustrate the critical role of *flow–structure interactions* in generating scour. The impact of skewed flow incidence, as represented by the angle of attack, and flow contraction due to multiple piers, underscores how localized hydraulic accelerations and vortex formations can significantly amplify scour intensity. These results stress the need for precise geometric representation in bridge hydraulic analysis.

Altogether, these insights contribute to a more robust understanding of scour dynamics, aiding engineers in the development of safer and more resilient bridge designs under increasingly variable hydraulic conditions.

**Statistical validation of empirical models using correlation metrics**

This section presents a statistical correlation between scour depth predictions made by the HEC-RAS model and those from empirical equations. The primary focus is on reporting coefficient of determination ($R^2$), which quantify the linear agreement between model predictions and empirical values

Various methods have been developed for performing regression analysis. Commonly used approaches, such as linear regression and ordinary least squares (OLS) regression, fall under the category of parametric methods. Correlation serves as a statistical measure to evaluate the strength and direction of a linear association between variables. When the underlying relationship is non-linear, the coefficient of determination ($R^2$) may not provide an accurate representation of the association. An observed correlation coefficient approaching one suggests a robust linear relationship. As shown in Table 6, the Larras and CSU equations yielded the highest correlation coefficients of 0.9975 and 0.9951 respectively, indicating excellent agreement with the HEC-RAS predictions. The Ahmed model also exhibited a high correlation (0.9743), followed by Shen-Maza (0.9241), Inglis-Poona (0.9082), and Blench-Inglis (0.8905). Although the Froehlich model presented a slightly lower correlation (0.8539), it still indicated a reasonably strong alignment.

**Table 6: Correlation factor between HEC-RAS and other empirical models**

| Sl. No | Equation | Correlation factor |
|---|---|---|
| 1 | CSU | 0.9951 |
| 2 | Larras | 0.9975 |
| 3 | Ahmed | 0.9743 |
| 4 | Blench-Inglis | 0.8905 |
| 5 | Shen - Maza | 0.9241 |
| 6 | Inglis-Poona | 0.9082 |
| 7 | Froechlich | 0.8539 |

The present section rightly emphasizes the high correlation values (e.g., 0.9975 for Larras, 0.9951 for CSU), validating the robustness of the HEC-RAS model. A brief ranking of the models based on their correlation values (Larras > CSU > Ahmed > Shen-Maza > Inglis-Poona > Blench-Inglis > Froehlich) would reinforce interpretability for readers. While high correlation values suggest strong linear relationships, they may mask underlying non-linear discrepancies, especially in cases of extreme discharges or sediment variability. To improve the reliability of validation, the use of additional statistical indicators such as RMSE (Root Mean Square Error), MAE (Mean Absolute Error), could be recommended.

Ultimately, these results collectively confirm that the HEC-RAS model is well calibrated and capable of accurately simulating pier scour under varying hydraulic conditions. The high correlation values, particularly those exceeding 0.9, validate the robustness of the model and underscore its potential for practical application in bridge design, maintenance planning, and hydraulic risk assessment. However, it is noted that correlation primarily captures linear associations and may not fully account for nonlinear relationships, which could be present in complex flow-sediment interactions. Nonetheless, the validation confirms that the HEC-RAS model reliably reflects observed scour patterns and aligns closely with established empirical methods.

## CONCLUSION

Scour depth analysis is essential for understanding river morphology and ensuring the safety and structural stability of bridge piers. In this study, we utilized the HEC-RAS modeling tool to estimate scour depth and compared the results with seven established empirical models. The following key findings and engineering recommendations have emerged from the analysis:

1. It is strongly recommended that when planning parallel or adjacent bridges, the new structure should be positioned upstream of the existing bridge. This configuration minimizes adverse hydraulic interactions and reduces the risk of excessive local scour.

Constructing a new bridge downstream may exacerbate turbulence and sediment removal, potentially undermining pier stability.

2. An increase in either the flow angle of attack or pier diameter significantly increases scour depth. Therefore, bridge designs should minimize flow obliquity and consider optimized pier shapes and sizes to reduce scour vulnerability.
3. Scour depth tends to increase when the river's cross-sectional breadth decreases. Hence, designs in narrow river reaches should incorporate enhanced scour protection measures such as riprap armoring or guide banks.
4. Higher flow discharge, depth, Froude number, and Reynolds number all correlate with increased scour depth. These parameters must be carefully considered in hydrologic and hydraulic design, particularly in regions prone to extreme flows.
5. The HEC-RAS model predictions showed strong agreement with empirical equations, especially the Larras (1963) and CSU (1975) models. Among these, the Larras model demonstrated the best correlation, indicating its practical reliability for similar riverine conditions.

This study enhances scour depth prediction by comparing HEC-RAS results with seven empirical models, identifying the Larras (1963) and CSU (1975) equations as most consistent. It offers practical guidance by recommending upstream placement of parallel bridges to reduce scour risk and emphasizes the influence of key hydraulic and geometric parameters. Future research should address sediment variability, climate change impacts, and complex flow interactions using advanced 3D modeling, while also evaluating the performance of scour protection measures under varying hydraulic conditions to support resilient bridge design.

**Declaration of competing interest**

The authors declare that there are no known financial or personal conflicts of interest that could have influenced the research presented in this paper.

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