A Risk-Based strategy for the Scour Analysis around bridge piers

Dalal Biswajit and Deb Subhrajyoti *
Department of Civil Engineering, ICFAI University Tripura, 799210, INDIA
*debsubhrajyoti60@gmail.com

Abstract
Local scour around bridge piers, especially during high floods, has been a critical issue for both the safety and serviceability of bridge foundations for decades. The objective of this study is to implement a risk-based strategy to account for local scour near the bridge piers. The methodology comprises of four fundamental steps wherein the first step involves evaluating hydrological hazards of an extreme nature. To precisely estimate the behavior of the river, the second phase uses several flow properties and depth of scour. In the third phase, the risk of scour connected with the bridge is evaluated by comparing the scour depth (D_T) with foundation depth (D_F) with a prioritizing factor (P_F) which aids in determining the qualitative assessment of the scour risk. Lastly, an assessment of the risk of scour rating is assigned to find out the severity of the scour risk for the bridge piers.

The present research discusses the incorporation of uncertainty in hydrological modeling through a predictive approach in the definition of the return period. To simulate flow parameters and assess bridge scour, the HEC-RAS program is utilized which incorporates a scour module. The study concludes with a qualitative evaluation of the impact of scouring on bridge susceptibility and safety. A case study on the Netaji Subhas Bridge across the Gomati (Gumti) river, Tripura served to validate the risk-based technique and it has been suggested that it can be effectively integrated into routine schedules for bridge examinations as a reliable risk management tool to avoid disastrous incidents.

Keywords: Local scour, Design period, HEC-RAS, Risk rating, Netaji Subhas bridge, Scour risk.

Introduction

The scouring process, triggered by the erosive power of water, can severely undermine the stability of bridge piers or abutments, particularly during periods of flooding or heavy precipitation. When bridges collapse, the consequences are felt far beyond the physical damage, as trust in infrastructure and public safety is eroded along with the debris. There exist various reasons that may lead to the failure of a bridge, but among them, the most prevalent is the scouring that occurs locally around its foundation[1]. Due to the lack of understanding of hydrological and hydraulic variables, there is still uncertainty in the design of bridge piers and intensifying floods make bridges more susceptible to scour effects[2-5].

Over the past thirty years, more than a thousand numbers of bridges have experienced catastrophic failures, with nearly 60% of these occurrences attributed to scour at the foundation of the bridge structure[6,63]. One of the causes of bridge collapse has been identified as scouring, accounting for more than half of all known collapses worldwide, according to a thorough study of the literature on global bridge collapses conducted by Benkaci [7]. Some notable incidents of bridge failure due to scouring in recent years in India are the Mahad Bridge collapse in Maharashtra (2016), the Savitri River Bridge collapse in Raigad, Maharashtra (2016), Bijanbari Bridge collapse in Darjeeling, West Bengal (2019) and Banihal-Qazigund highway bridge collapse in Jammu and Kashmir (2021).

Current guidelines for designing and building bridges often suggest that the structures should be able to withstand a flood with a specific likelihood of occurring within a certain period, usually between 100 to 200 years[9-11]. This likelihood is determined by statistical models that estimate the frequency and severity of floods based on historical data. Some recent studies have found that the current design guidelines for bridges which consider only a fixed return period, do not take into account the variations in the time it may take for a bridge to fail or collapse due to scouring effects[8,12,13]. Due to the rise in the occurrences and strength of floods, it is needed to consider and mitigate the risk of scouring to ensure that the bridges are safe and can withstand flooding[8].

It is challenging to entirely remove the potential danger of scour, but a detailed evaluation of the risk is necessary for developing design standards and inspection practices. Based on the assessment, design criteria can be established to ensure that the structure is resilient to scour. The hydraulic as well as hydrological variables are among the most critical reasons that can affect the safety and stability of bridge foundations[16,17].

However, these variables can also be difficult to accurately predict or measure, leading to uncertainties in the design process[14,15].

Scour risk is inherently stochastic and accounting for this uncertainty is crucial for a more accurate assessment of the risk and the development of effective mitigation measures. A risk-based approach can improve scouring assessment and lessen the susceptibility of bridges to scouring effects by taking into account the ambiguity of both hydraulic and hydrological parameters.

A risk-based methodology involves quantifying the probability and consequences of scour-related failure events and determining an acceptable level of risk[18]. This approach considers the uncertainty in the input variables and gives a more realistic prediction of the likelihood and severity of scour-related failure events. By accounting for uncertainty, engineers can develop more targeted and cost-effective mitigation measures to reduce scour risk[19,20]. For example, a risk-based approach may identify specific sections of a river or channel that are more susceptible to scour and prioritize the implementation of protective measures in those areas.

Some previous researchers have discussed the importance of a risk analysis framework in identifying and mitigating risks associated with hazardous events, particularly in the context of infrastructure[21,22]. The framework combines hazard analysis which identifies the likelihood of a hazardous event occurring and vulnerability assessment which focus on factors that shape the susceptibility of infrastructure to such events[16]. Barbetta et al[6] presented two methods for assessing bridge pier vulnerability to scour, with one method yielding quicker results than the other. A structural evaluation is likewise included in a bridge safety inspection technique. Due to the chaotic character of hydrological events, it is difficult to predict what causes susceptibility and how the system will react to these occurrences, particularly when environmental circumstances are worse than expected.

Overall, a risk-based methodology that accounts for uncertainty can provide a more accurate assessment of scour risk and help engineers to develop more effective mitigation measures. This strategy can eventually make bridges less susceptible to scour effects and improve the security and dependability of infrastructure projects.

The objective of the current study is to develop an organized approach to determine how bridge scouring impacts the stability of the bridge with the associated level of risk. This entails a four-step technique. The first step involves identifying extreme hydrological events that result in river floods through data collection from the field and modeling of hydrological parameters. Subsequently, in the second step, the river behavior is simulated by computing the flow parameters and bridge scour variables. In the third step, the ratio between the depths of scour to the depth of the foundation is correlated with a prioritizing factor that takes into account relevant features that may vary the severity of the failure which include foundation type, materials on which the structure is built, or the history of scouring.

Lastly, an assessment of the risk of scour rating is assigned to find out the severity of the scour risk for the bridge piers. This approach is used to assess the likelihood that a bridge may experience scour. The methodology also involves a qualitative assessment of the 'level of risk' or the ‘degree of risk’ connected to scouring. By utilizing this methodology, it is feasible to assess the impact of bridge scouring on bridge stability and ascertain the level of danger which can facilitate the development of appropriate mitigation measures to ensure bridge safety.

The present study involves the analysis of various probability distributions to accurately quantify the highest discharges that converge at the cross-section of the bridge. These design floods are subsequently employed to compute relevant flow variables such as approach flow depths and velocities as well as the scour depths. The modeling of scour near structures built on alluvial beds is prone to major unpredictability, so it needs to be highlighted. While modeling mistakes are related to the chosen scour computation approach, such ambiguities are fundamentally linked to the hyper parameters used in the modeling process[23,24].

The HEC-RAS software[25] is taken into account to calculate the maximum scour depth as part of the suggested technique and these depths are then tested with other empirically oriented predictors[26] concerning the respective fluid properties and geometry of the bridge substructure. The scour risk level is then calculated by comparing the local scour depth at the bridge bottom to the corresponding foundation depth. A real application of the suggested technique was made for the Netaji Subhas bridge in the Gomati (Gumti) river, Tripura as a means to confirm its efficacy.

Material and Methods

Methodology: The process of risk analysis of bridges typically has two stages: risk assessment and risk management[18]. In the risk assessment stage, the probability and potential consequences of bridge failure are evaluated based on various factors such as the design of the bridge, its age, maintenance records and exposure to natural disasters[27]. In the risk management stage, strategies are developed to minimize the level of risk associated with the bridge. These strategies may include repairs, maintenance and monitoring programs to detect potential issues before they become critical.

There are two different methods for evaluating risks: quantitative risk analysis and qualitative risk analysis[28]. To determine the likelihood and seriousness of threats, qualitative risk analysis uses expert judgment and subjective assessment while quantitative risk analysis is a more data-driven approach that uses mathematical models and statistical methods to analyze the likelihood and impact of risks. Both methods have their strengths and weaknesses and the choice of method depends on the specific situation and available resources[1].

The current study presents a comprehensive methodology for assessing the dangers of scouring at bridges, utilizing a qualitative risk approach. The method incorporates simulation of the hydraulic as well as hydrological properties of river systems while considering the geometry of the bridge and site-specific factors. However, there has been no examination of socio-economic consequences. Such an impartial analysis of the possible financial implications linked to various degrees of destruction of infrastructure from scouring would be necessary for such an estimate as well as intangible costs such as operational interruptions and possible loss of life in the event of failure. The four main stages that make up the suggested risk analysis technique are depicted in fig. 1. Since these issues fall outside the scope of this investigation, fig. 1 specifies the requirements, procedures and results for each stage.

The technique proposed in the present study aims to predict risks by bridge scouring resulting from extreme hydrological events, using a quantitative approach. In the first step, the rate of flood episodes is determined by statistically analyzing the maximum yearly inflow data at the bridge location, taking into account the peak flows and return period. The hydrological events are then used in the second step to derive the corresponding hydraulic parameters, utilizing the freely available HEC-RAS software (6.2 version) created by the US Army Corps of Engineers and the Hydrologic Engineering Center (CEIWR-HEC), providing the inlet flow depth and velocities at the bridge location[25].

In the third step, the depth of local scour near the bridge piers is evaluated using fluid flow characteristics, sediment properties and the geometry of the bridge is considered. The ultimate scour is calculated using the HEC-RAS scour computing capacity and the results are correlated with suitable empirical techniques[26,29]. The final step compares the maximum depth of scour (calculated by adding local and contraction scour) to the equivalent depth of foundation (relative scour depth) and a qualitative risk evaluation is used to calculate the possibility of foundation failure due to scouring[10].

Hydrological modeling: The purpose of hydrological modeling is to acquire a dependable estimation of the likelihood of extreme discharge flows occurring at a specific location such as a bridge site. These extreme flows are commonly known as "design floods," and to assess them, statistical methods are usually employed which are commonly referred to as "flood frequency analysis"[31-33].

The flood frequency analysis is a fundamental procedure for estimating extreme discharge flows and their corresponding probabilities at a specific location such as a bridge site. Various statistical models are employed to represent the observed data and the present methodology suggests six probability models: two and three-parameter Log-Normal, Gamma, Weibull, Gumbel and LogPearson III distributions. Hydrologists frequently advise using these methods in *in situ* and region-specific scenarios[34-37]. Moments, maximum likelihood and L-moments are frequently used to calculate the variables of each probability distribution function[38]. The effectiveness of these methods is then judged using graphical tools and goodness-of-fit tests[39].

However, uncertainties exist in any model and to assure the quality and utility of the data, it is crucial to quantify these uncertainties[40]. To address this issue, Hoeting et al[30] suggested all candidate probability distributions to estimate design floods, through a process called model averaging. Model averaging can be done either by arithmetically averaging the design discharge projections from each candidate model, depending on how closely the candidate probabilistic models resemble the data[41,42,44].

When dealing with small sample sizes, Miner et al[44] suggested that choosing the probability distribution with the best fit may be linked to outliers (30–50 hydrological years). Hence, the modified arithmetic averaging approach (M.M), introduced by Mohammadpour et al[45] is used in the current methodology. This updated M.M. method ensures the selection of the best appropriate probability distribution for predicting design floods by only taking into account distributions that pass both graphical methods and goodness-of-fit tests. The outcome of this first step is defining the design flood using the modified M.M.

Model development and scour analysis: Hydraulic modeling plays a vital role in comprehending the spatial and temporal variations in the hydrodynamic behavior of rivers and their impacts on the surrounding ecosystems. The evolving dynamics of a river system, triggered by anthropogenic interferences, topographic modifications and environmental factors, contributes to higher erosion and deposition rates. These changes, in turn, significantly alter the morphology of the riverbed and may pose a potential risk to the stability and resilience of bridge foundations, particularly in the form of scouring effects.[45]

The suggested technique utilizes the HEC-RAS model to simulate the spread of design flooding towards a particular bridge segment. Studies have thoroughly verified the popular tool HEC-RAS for 1-D and 2-D hydraulic simulation[17,46-48]. A comprehensive description of HEC-RAS modeling capabilities can be found in Brunner's work[15]. The use of HEC-RAS in the present study aims to provide a reliable estimation of flood behavior near the bridge site taking into account factors such as river morphology and hydraulic properties.

The suggested methodology constantly uses constant flow parameters within the HEC-RAS river investigation component to maintain simplicity and resilience. This strategy has been employed by regulatory bodies frequently[49] and has been applied in the investigations[46,48]. The constant flow element can simulate a variety of flow regimes including mixed, subcritical and supercritical flows[50]. It is worth noting that subcritical flow is the most commonly encountered regime in large bridges worldwide.

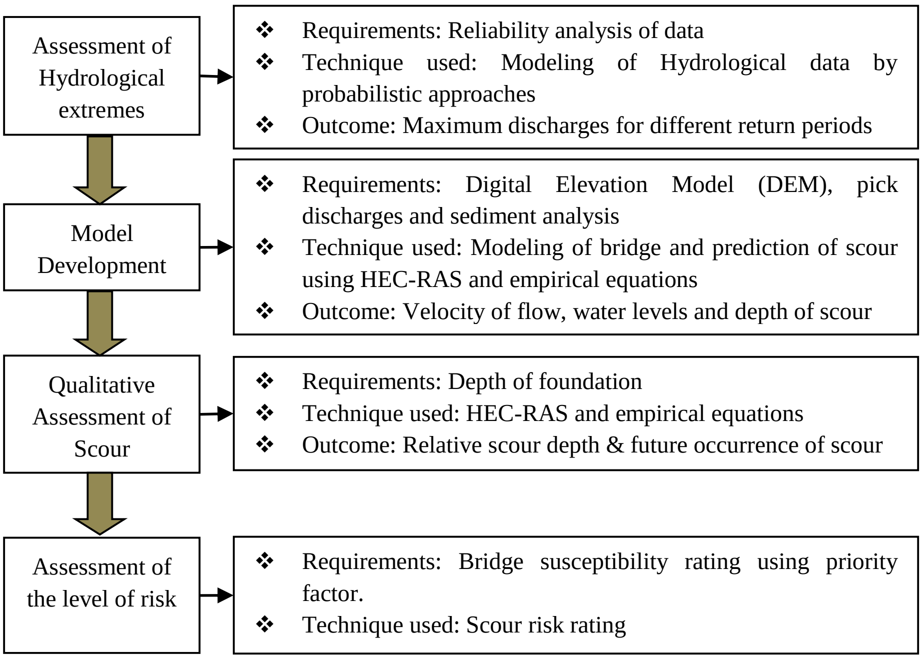


Figure 1: Methodology for risk assessment of bridge scouring

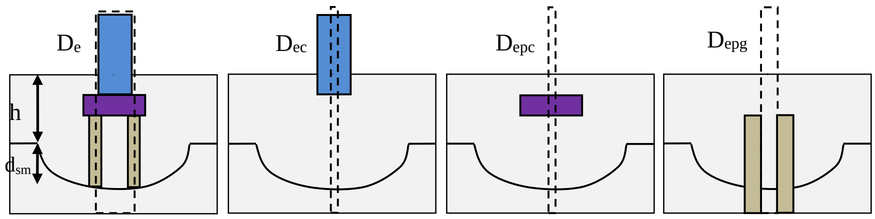


Figure 2: A conceptual explanation of how to calculate De using the total of the individual diameters of each pile-supported component; the column, pile cap and pile group is provided. While factor h represents approaching water depth, d_{sm} represents the maximum local scour depth (Motivated by Moran)[47].

The precise identification of the morphology, upstream and downstream boundary conditions and stream attributes is required by the hydraulic model used in this work[25,50,51].

A suitable level of input processing of the bridge geometry and river bathymetry is required for spatial input data that capture river characteristics, inflow and sediments in both floodplain zones and river beds.

Hydraulic modeling largely depends on the assessment of channel roughness for the precise measurement of water surface heights and flow rates. Channel alignment, surface roughness, vegetation cover, scour and deposits, channel irregularities, obstacles, channel size and form, stages and inflow, seasonal fluctuations, heat, suspending material and bed load are just a few of the variables that have an impact on this parameter[52-54]. When possible, it is advised to validate the roughness coefficient utilizing field data instead of the conventional value for different watershed parameters.

McKay and Fischenich[41] provided a thorough discussion of roughness prediction methods and the underlying theories. Both the median particle sizes dimension D_{50} and the D_{90} can be used to describe the stream bed. The surface of the water profiles and associated flow rate for various design flooding can be estimated after the hydraulic model has been calibrated. Many formulas have been put forth over the years to calculate the maximum local depth of scour, with projection abilities often suitable for constructions with straightforward geometries. According to Sturm et al,[58] the empirical estimations provided in the most recent iteration of the Melville/Sheppard (M/S) equation and HEC-18 (old) equation are advised for bridge piers with basic shapes[26]. Using the techniques of the Florida Department of Transportation, FDOT, HEC-18 (new) and techniques of Yang et al[66] may require modifications for pile-supported piers such as taking an equivalent diameter, D_e (Fig. 2) into consideration. Using these empirical predictors, clear water and live bed scour conditions both can be estimated.

A bridge-scouring computing technique is offered by the HEC-RAS software and is accessed from the "Hydraulic Design Functions" window. This procedure uses a variety of empirical methods including those suggested by the earlier iteration of the HEC-18 equation, to calculate the maximum depth of local scour[56]. Laursen's clear water equation[37] and Laursen's live bed equation[38] are used by HEC-RAS to assess the contraction scour. Although some scholars have questioned this assumption, the overall scour depth at bridge piers is measured by summing the contraction and local

https://doi.org/10.25303/174da053067

scouring. This method assumes that each scour process is distinct[26]. The process generates final assessments of the local scour depths for the most vulnerable foundation, enabling the rating of scour risk.

Risk rating of scour: Bridge safety is significantly impacted by the relationship between the permissible range of depth of scour and the depth of bridge footing[64]. This critical ratio is denoted by the relative scour depth metric $D_R = D_T/D_F$ where D_T is total scour depth and D_F indicates foundation depth. D_F is an important aspect in assessing a bridge's scour resistance and the possibility of scour-induced failure. D_F is calculated differently depending on whether the foundation is simple or piled and if the piles extend to the lower bed strata below. For a fundamental foundation, D_F is calculated out from the mean river bed to the underneath of a shallow foundation (as shown in fig. 3a). For deep foundation, D_F is determined by comparing the mean bed level to the pile-lowest cap's point (as shown in fig. 3b). While pile-supported foundations are less prone to scour-related collapse, exposing the piles themselves is still negative since it might impact the bridge's carrying capacity or lateral stability.

In such instances, the estimation of D_F must take into account all thick layers of alluvial deposits in the area of the foundation (as indicated in fig. 3c). Apart from the previously described hydraulic features of the flow, various other factors may contribute to an increased or decreased risk of failure. Although considering these elements may be more difficult, they must be considered.

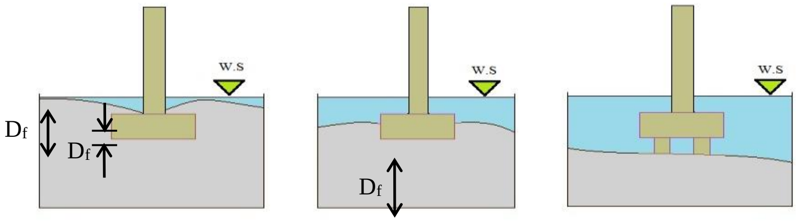


Figure 3: Description of the height of foundation (D_F) based on the alluvial riverbed levels from (a) to (c); surface water is denoted by W. S.

Table 1
Values for the variables that affect the Priority factor[29]

Type of foundation, F	
Deep (piled)	F = 0.75
Shallow (spread)	F = 1.00
Past record of scour problem, H	
If the bridge has no history of problems	H = 1.00
If the bridge has a history of scour problems	H = 1.50
River bed material, M	
There is convincing proof the bridge is built of clay, or there is a good chance that the foundations may be made of rock.	M = 0.50
There is substantial proof that the bridge is over clay foundation	M = 0.75
The nature of the material is unknown.	M = 1.00
Type of river, T_R	
The terrain is lowland	T_R = 1.00
The terrain is hilly	T_R = 1.20
The terrain is upland	T_R = 1.30
The terrain is mountainous	T_R = 1.50
Other factors, V	
SH/ODR (12H traffic flow ≤ 1 000)	V = 0.70
NH/ SH (12H traffic flow: 1 000–9 999)	V = 0.80
Expressway/ NH (12H traffic flow: 10 000–29 999)	V = 0.90
Expressway (12H traffic flow ≥ 30 000)	V = 1.00

https://doi.org/10.25303/174da053067

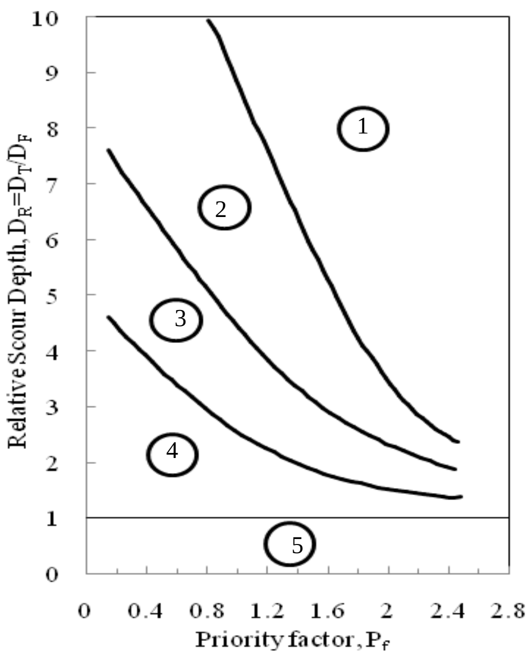


Figure 4: Scour risk rating[29].

Table 2
Principal benefits and drawbacks of the suggested risk-based technique

	Assessment of design return period	Model Development	Assessment of scouring risk of bridge
Advantage	By using the modified MM technique, design floods are estimated while taking hydrological uncertainties into account.	An HEC-RAS modeling tool that can predict scour is freely available and is supported by current and sufficient empirical predictors.	The estimation is accurate of the scour's relative depth and how it affects the depth of footing that is available.
Limitation	It assumes the peak discharge as an independent variable.	It assumes the addition of contraction and local scour as an independent process.	The existence of trash or obstacles is not taken into account when calculating the priority factor for the bridge.

These factors are listed by the Highways Authority[29] as follows: (I) Type of foundation (F), (II) History of scour problem (H), (III) River bed material (M), (IV) Type of river (T_R) and (V) other factors. These standards can be put together to generate the priority factor (P_f), which would be stated as P_f = $FHMT_RV$ and is employed to assess the vulnerabilities of an infrastructure. A complete list of these factors and their description can be found in table 1.

A bridge's scour risk rating is calculated by comparing the respective depth of scour (D_R) and the priority factor (P_f) which provides an estimate of the probable risk level. Figure 4 depicts the risk rating on a graph with five bands ranging from 1 (highest risk) to 5 (lowest-risk).

A case study on the Netaji Subhas Bridge

Selection criteria: To conduct a thorough risk analysis for the proposed work, the selection of the bridge on river Gomati river was considered. Given the complex nature of the site and bridge-specific cases, an extensive investigation was conducted to ensure the selection process. Factors such as the availability of monitoring data and susceptibility to the scouring phenomenon were evaluated before the selection process.

To proceed with the analysis, specific data was required. This included detailed bathymetry of the upstream, bridge and downstream sections as well as the structural characteristics of the bridge's substructure and superstructure components. It was also essential to have access to the sieve analysis data near the bridge foundations and uninterrupted observations of inflows at an adjacent gauge station, particularly at the time of floods. The variation in bed level at the bridge location over time was taken into consideration.

The choice of the case study was made in collaboration with the gomati barrage Subdivision authority (Meghna Division,

https://doi.org/10.25303/174da053067

Silchar). The assistance of the personnel from the division ensured that data specific to the required conditions and requirements were available. Multiple potential bridge case studies were considered and after a thorough evaluation process, the Gomati River's Netaji Subhas bridge was chosen as the best location for the empirical studies on the relationship. The coordinate of the bridge is 23.544885˚ N, 91.481256˚ E. The selection process was conducted to ensure that the chosen case study was the best fit for the proposed investigation.

Hydrographic region characterization: The Gomati (Gumti) river, located in the northeastern Indian state of Tripura, is a major river system with a total length of 133 km. The river originates from the Atharamura hills and flows through the districts of South Tripura, Gomati and Sepahijala before it enters Bangladesh and joins the Meghna river. The river basin covers an area of 2378 square kilometers and the river has been extensively studied to understand its hydrology, ecology and water resource management.

Based on terrain and land usage, the Gomati river basin can be categorized into four separate watersheds: the Upper Basin, Middle Basin, Lower Basin and Estuarine Zone. Atharamura, Longthorai and Baramura, three hilly regions where the river begins are included in the upper catchment area. The uneven fields on the east and west sides are comprised of the middle catchment zone whereas the southern plains of the basin are covered by the lower catchment region. The underside of the river, where it merges with the Meghna river, is included in the estuarine zone. The Gomati river basin consists of dams, bridges and other infrastructure.

The Netaji Subhas bridge is located on the 119.52 km downstream side of Gomati hydro dam, popularly known as Dumbur dam which is located in the middle catchment region and used for hydroelectricity generation, drinking water and irrigation purpose (Fig. 5)[26].

The Gomati river also flows through several bridges including the Subhas Bridge, which is between Agartala and Udaipur. The flow impacts on the bridge are primarily determined by outflows from the Dumbur dam on the Gomati river[26]. The sediment values in the Gomati river basin vary depending on the location and season.

According to a study by Bhattacharjee et al,[11] the sediment yield in the upper catchment region is relatively low due to the forest cover and topography, while the sediment yield in the middle and lower catchment regions is higher due to agricultural practices and urbanization[60,67]. The study also found that the sediment concentration in the river water increases during the monsoon season, indicating high erosion rates in the catchment areas.

The Gomati river basin in Tripura has a real-time hydro-meteorological network established by the Central Water Commission (CWC) of India for the river's flow and water quality parameters. The network consists of several monitoring stations located along the main stem of the river and its tributaries and data from these stations is transmitted in real-time to the CWC's National Water Informatics Center. The real-time data from the hydro-meteorological network provides valuable information for managing the water resources of the Gomati river basin. The data is used to forecast floods, droughts and water availability and is also used for water allocation and irrigation planning. Real-time monitoring of water quality parameters such as pH, dissolved oxygen and total suspended solids is also important for managing the water resources of the basin.

Bridge Characteristics: Subhas bridge is a major bridge located on the Gomati (Gumti) river in Tripura, India. The bridge connects the cities of Amarpur, Udaipur and Sonamura. The total length of the deck of Netaji Subhas bridge is 120 meters. The bridge has a width of 8 meters with a 7 m single-lane and two-way carriageway for vehicular traffic. The formation level of the bridge is 24.50 m where freeboard of 2.4 m is provided.

To make construction easier, the foundations for the Netaji Subhas bridge were constructed lengthwise just outside of the previous bridge piers. Comparable bridge spans were also taken into consideration, but they were distributed between the mid-range as well as the outliers more evenly[62].

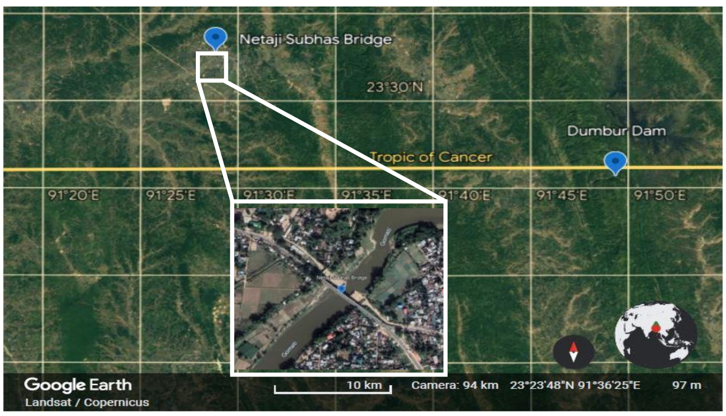


Figure 5: Study Area (Netaji Subhas Bridge, over the Gomati River)

Figure 6: Pictorial view of Netaji Subhas Bridge over the Gomati River

Table 3
Dimensions of Netaji Subhas Bridge

Dimensions of Bridge (m)				
Deck dimensions			Pier's Elevation	
Length of bridge	Width of bridge	Thickness of deck	Pier - 1	Pier - 2
120	8	2	34.7	34.7

For making the link between the old and new abutments feasible, special attention was paid to align them with the length of the bridge deck as a whole. Using a progressive launching approach of the steel structure eventually transforms into a hybrid steel-reinforced concrete structure built on a 22 m thick alluvial deposit stratum. Fig. 6 illustrates a bridge that is sustained by two lateral abutments and two piers that are positioned in the main stream. Table 3 provides further dimensions and lists the bridge piers in numerical order from the right embankment to the left embankment.

The bridge pier P_2 (Fig. 6) was taken into account for such risk analysis because it is the pier that seems to be more susceptible to case study scour attributable to its location to the streamlines. Pier P_2 is an end-bearing pile built on an alluvial deposit layer that is 22 m thick. The geotechnical and geological portion of the executing project generated this information[61].

Results and Discussion

Hydrological model development: The study took into account gathered hydrological data from three gauge stations in the proximity to the Netaji Subhas bridge, identified as "Amarpur (GBS) - QA," "Udaipur (GBS) - QU," and "Maharani (GBS) - QM" (Fig. 5). QA, QU and QM represent the stream flows extracted from these stations which could indicate the average daily and instantaneous data. The average daily datasets were gathered from the Climate Forecast System Re-analysis (CFSR) platform, while the instantaneous data were made available by Gomati Barrage subdivision (GBS), the entity responsible for managing the dams used in the study. Only records between 1986 and 2020, which represent 35 years of hydrological data, were used for the analysis after verifying data quality, record length and data gaps.

Additionally, the promise of randomness, consistency and continuity was supported. The study took into account various hydrological situations to assess the peak yearly discharge flow approaching the Netaji Subhas bridge (QS) and the sum of the records (QC + QT + QFT) was utilized to calculate QHR. The results and determination of QHR for each situation are given by Bento et al.[8]

In reference to the work conducted by Bento et al[8] and its corresponding results, the analysis in this work only pertains to the hydrological scenario estimated from the instantaneous discharge data. For the period between 2007 and 2020, the instantaneous discharge data for QC and QT were available. However, for the remaining period between 1986 and 2006, the instantaneous discharge data was approximated by establishing proportional relationships between the average and instantaneous records for the respective measuring stations of QC and QT.

The validity of this approach was confirmed using the records obtained from a neighboring station of QT, known as the gauging station of "Sonamura (GBS) - QS" which provided both mean and instantaneous discharge data.

Further information on this methodology can be found in study of Bento et al.[8]

This analysis considered seven return periods denoted as T = 5, 10, 20, 50, 75, 100 and 200 as shown in table 4. Four of the six parametric distributions covered in this study are: the Gumbel, Log Normal (2p and 3p) and Gamma distributions which produced adequate results. The design floods derived using either the modified MM technique or the best-fitted distribution (M.S) are shown in table 4. The Gamma distribution provided the best fit to the data under analysis and was used to estimate the MS design floods. The maximum annual instantaneous flow observations made close to the Netaji Subhas bridge were subjected to goodness-of-fit tests which validated the applicability of this probabilistic model.

Additionally, the graphical adjustment obtained from the Gamma distribution outperformed the other probability models. Benkaci's free MATLAB code was used to perform the flood frequency analysis. [7].

In the study, the range of MS discharge readings was found to be 1084 m^3/s for a 5-year return period to 1937 m^3/s for a 200-year return period. Meanwhile, using the improved M.M technique, the estimated design floods ranges from 1057 m^3/s to 2345 m^3/s respectively as shown in table 4. The highest flood on record was in 1981, with a magnitude of 1495 m^3/s, according to the DPR (Detailed Project Report) of Netaji Subhas bridge. This discharge value is approximately equivalent to the design flood obtained for a 20-year return period using both methods.

"Relative disparity" between the M.S. and improved M.M. techniques is seen in table 4. The "relative disparity" ranged from 3.2% to 17.4% for return times of 20 to 200 years. The improved M.M technique estimated the flooding forecasts for RP=5 years and RP=10 years in comparison to the M.S methodology. The improved arithmetic model averaging (improved M.M) approach which generated larger inflow values (Table 4), notably for higher return durations, presents the worst-case scenario in line with the study's ultimate goal. The modified M.M. approach takes into account model uncertainty brought on by models' inability to faithfully describe real-world occurrences. Mathematical models always simplify reality which introduces uncertainty. As a result, only the outcomes of the modified M.M. technique were taken into account for the remaining phases.

Hydraulic model development: Based on Chow's[20] recommendations, the roughness coefficient was calculated. According to these recommendations, the riverbanks were given a coefficient of roughness of 0.040 $m^{-1/3}s$ while the main channel received a value of 0.033 $m^{-1/3}s$. Water level information from the 1981 flood and the lengthwise sediment bed profile at the bridge place were used to calibrate the coefficient of roughness at the main channel. These supported the preliminary estimate. Yan et al[65] provided a rating curve that was taken into consideration for the downstream boundary condition.

In order to replicate steady flow regimes extending from Q5 to Q200, a 1D hydraulic model was taken into consideration. The current study measured local hydraulic parameters such as flow velocity, flow depth and Froude number, in the area of Pier P_2 for each flooding design. The results of using these values to assess scour depth are shown in table 5.

The median grain size (D_{50}) was determined to be 0.65 mm while the D_{90} was 2.01 mm, based on information obtained from the sieve analysis after collecting the sediment sample near the bridge pier. To calculate the total depth of scour (D_T) at the beginning of Pier P_2, this information was required.

The hydraulic parameters and scour predictions at the position of P_2, as determined by the HEC-RAS scouring module, are presented in table 5. The corresponding equivalent diameters (D_e) were established before determining the extent of scouring depth. The modeled flow rates were found to be between 1.42 and 2.71 m/s with subcritical flow regimes and Froude numbers under 1. Except for the 5-year return period flooding, which took place in clear water, the design floods were seen to occur within live bed conditions. The water level associated with the Q5 to Q200 return period is shown in fig. 7. The hydraulic factors and associated scour estimations near P_2 are summarized in table 5, with the appropriate equivalent diameters (D_e) computed before scouring depth calculations.

Table 4
Netaji Subhas Bridge design floods (Q_{NS})

Return Period (years)	Q_{NS} (m^3s^{-1})		Relative change (%)
	M.S	M.M	(M.M-M.S)/M.M
Q5	1083.858	1057	-2.5
Q10	1252.335	1247	-0.4
Q20	1413.941	1461	3.2
Q50	1623.145	1773	8.5
Q75	1714.927	1924	10.9
Q100	1779.901	2041	12.8
Q200	1936.097	2345	17.4

https://doi.org/10.25303/174da053067

Table 5
Depth of scour at pier P_2 using the HEC-RAS model with other hydraulic parameters

Return Period	Water Depth	Equivalent Diameter	Velocity of Flow	Froude Number	Depth of scour (contraction)	Depth of scour (local)	The total depth of scour
	(m)	(m)	(m/s)	(F_r)	(m)	(m)	(m)
Q5	10.25	3.25	1.42	0.29	0.75	5.42	6.17
Q10	11.68	3.25	1.67	0.29	0.94	5.55	6.49
Q20	12.17	3.25	1.81	0.31	1.15	5.60	6.75
Q50	13.08	3.25	1.95	0.33	1.27	5.76	7.03
Q75	13.86	3.25	2.17	0.34	1.35	6.03	7.38
Q100	14.42	3.25	2.43	0.35	0.94	6.67	7.61
Q200	15.89	3.25	2.71	0.37	0.94	6.99	7.93

The overall scour depth was calculated using HEC-RAS to preserve the straightforwardness and applicability of the methods. The HEC-RAS scouring module made it easier to determine the local and contraction scour depths which are shown in table 5. The level of contraction scouring was found to be noticeably less than the comparable local scouring depths by an order of magnitude. This led to the conclusion that the estimations of local scouring were far more important than the contraction scour depths. It should be noted that the contraction depth of scour for Q100 (0.94 m) was considered to be equal to the contraction depths for the return period of Q200 in this study due to restrictions related to pressure flow scour.

The HEC-RAS approach which uses a previous version of the HEC-18 equation[56] to calculate the ultimate depth of scouring, was used to estimate the local scouring component. The observed scour depths have been compared with those predicted by three other empirically produced formulations, including Yang et al[66], FDOT [55] and HEC-18 predictors [9], to evaluate the effectiveness of this method. Figure 8 shows the outcomes of these comparisons.

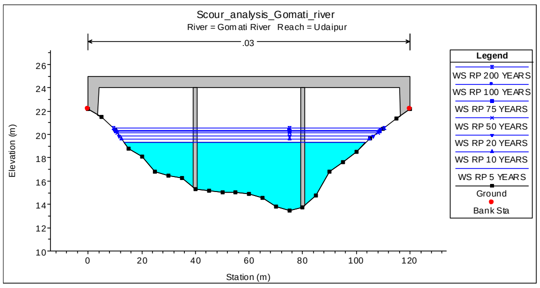
Regarding the rise in the design flooding conditions, the HEC-18 calculations[56] show a noticeable rise. Furthermore, the largest return period is taken into account. Q200 does not cause the ultimate depth of local to scour to reach its peak; rather, it would continue to rise as the likelihood of hydrological extremes decreased, albeit at a slower rate. The estimates of the other predictors are significantly inflated by this version of the HEC-18 approach. Local scour depth estimates using the HEC-18 equation[9] correlated with the other empirical formulae looked at in this investigation. When compared to the previous version HEC-18 approach,[56] the rate of growth is noticeably reduced even if the scour depths obtained using this method still increase when the design flood conditions increase.

Across the range of design floods taken into consideration, the FDOT technique[55] estimates maximum local scour depths that are very consistent. In contrast, the approach used by Yang et al[66] shows a modest rise in the depth of scour between the 5-year and 10-year return period design floods, with a maximum depth of scour of 5.12 m and ranges around a central value of 3.82 meters from Q10 to Q50, after which the scour depth at the bridge foundation (P_2) exhibits deterioration. When compared to the HEC-18 technique[56], the estimations made using Yang et al method[66] underpredict the ultimate depth of local scour by 7% to 65%. The disparities between the FDOT technique estimates and those of Richardson and Davis[54] are significantly greater ranging from 30% to 60%.

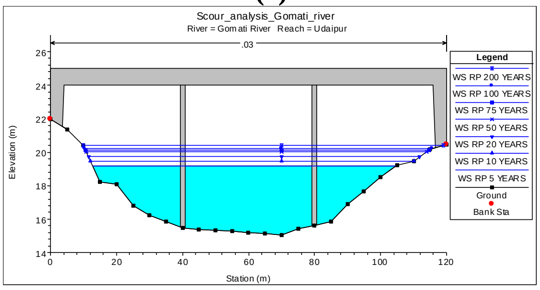
In addition to the visual evaluation shown in figure 8, the accuracy of the estimates regarding the results of the HEC-18 [56] was evaluated by the calculation of RMSE (Root Mean Square Error). The estimated RMSE outcome for the HEC-18[9], Yang et al[66] and FDOT[55] techniques were 0.5971, 0.8627 and 0.9317 respectively. These results supported the discrepancies shown in fig. 8's illustration. An autonomous hydraulic model was created employing the topographical and bathymetric information collected from 2010 through HEC-RAS based on predefined assumptions. The major flow features and overall scour depths at P_2 were calculated using the flood events seen between 2010/11 and 2012/13. According to the results of the hydraulic modeling, the highest yearly discharges were between 1057 and 2345 m^3s^{-1} with flow depths between 10.25 and 15.89 m and F_r between 0.29 and 0.37.

Since the difference of less than 1 meter does not significantly affect the analysis of alluvial bed material change in the Gomati river, according to the examination, the scour results produced by the HEC-RAS modeling tool are compatible with the level of the scour that was observed[66]. Therefore, for future risk evaluations, which are covered, the ultimate depth of scour produced from the HEC-RAS model was utilized.

The level of scour risk: The depth of foundation at P_2 recorded in the DPR (Detailed Project Report) of the Netaji Subhas bridge (D_F = 12 m) was compared to the calculated ultimate depth of scour (D_T) for every return period given in table 5. This comparison, represented by the ratio D_T/D_F, was used as the primary parameter for prioritization (D_R) and is presented in table 6. The corresponding foundation depth (D_{FT}) and accompanying return period for every proposed flood are also included in table 6.



(a)



(b)

Figure 7: Model development in HEC-RAS software in (a) upstream (b) downstream

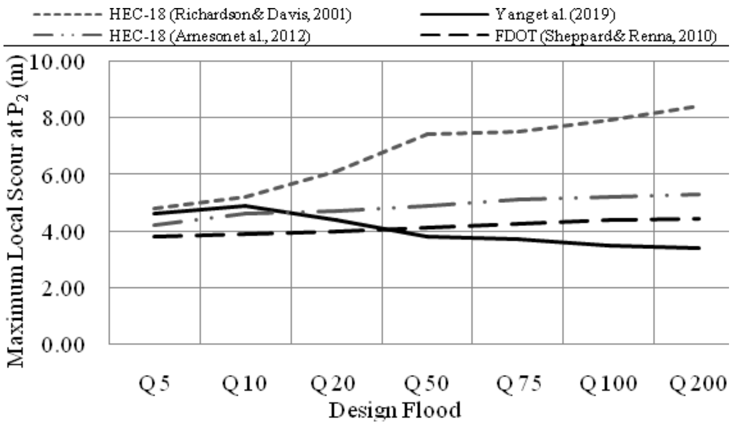


Figure 8: Local scour predicted using four empirical equations

Table 6
Risk rating of Netaji Subhas Bridge

Return period	D_T (m)	D_{FT} (m)	D_R (-)	Scour risk rating
Q5	6.17	5.83	0.51	5
Q10	6.49	5.51	0.54	
Q20	6.75	5.25	0.56	
Q50	7.03	4.97	0.59	
Q75	7.38	4.62	0.62	
Q100	7.61	4.39	0.63	
Q200	7.93	4.07	0.66	

Table 7
Factors contributed to find the priority factor of the Netaji Subhas Bridge

Factors	Symbols	Values
Deep foundation (piled)	F	F = 0.75
NH/ SH (12H traffic flow: 1 000–9 999)	V	V = 0.80
The bridge has no history of problems	H	H = 1.00
The terrain is lowland	T_R	T_R = 1.00
Material is granular	M	M = 1.00

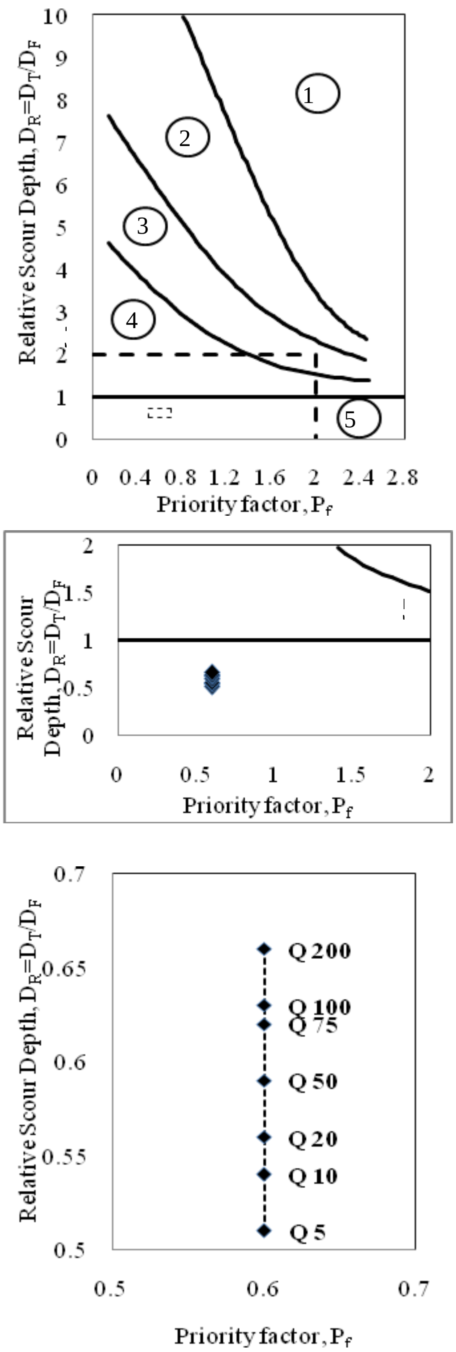


Figure 9: Rating of sour risk of the Netaji Subhas Bridge

The priority factor (P_f) for the Netaji Subhas Bridge was determined by combining the parameters listed in table 1 and was given as 0.60 in table 7. The type of foundation (F) is a more important factor compared to the pier type (P_2) for the pile-supported pier. The river type (T_R) at the bridge position and the riverbed material has a negligible effect on the priority factor. As per the Highways Agency's rules[29], a bridge's significance (V) is directly proportionate to the volume of traffic that crosses it. A traffic flow of 4,325 12-h was observed for the Netaji Subhas bridge and a V factor of 0.80 was assigned based on this observation.

As illustrated in fig. 9, the corresponding relative scour depth (D_R) and priority factor (P_f) values were used to calculate the risk rating for the Netaji Subhas Bridge. Based on the design floods analyzed in this study, the Netaji Subhas bridge was assigned a scour risk rating of 5. At this level of risk, routine inspections, which are conducted every three years by the National Authority, are sufficient, according to Indian Standards. In keeping with the recommendations made by the Highways Agency[29], it is crucial to remember that the acquired rating should be viewed as an estimate rather than a firm declaration of relative risk.

The relative scour depth was calculated using the foundation depths (D_F = 12 m) which were derived from the DPR, under the assumption that the design flooding was a distinct occurrence. However, it should be remembered that as the overall depth of scouring at P_2 elevates over time, the overall result of scouring may have a detrimental effect on the depth of the accessible foundation. The D_{FT} results shown in table 6 illustrate the impact of this cumulative effect.

Evaluating the pile's load-bearing capacity in geophysical design requires taking skin friction: the deployment of the pile's surface resistance as a result of interaction with the adjoining alluvial bed into account. However, it is customary to disregard the lateral pile resistance provided by the topmost few meters of the river bed. The top alluvial layer was not taken into consideration, owing to the geotechnical and geological portion of the bridge's construction project[61].

Conclusion

This study suggests a risk-based technique for determining the risks related to scouring around the bridge piers. In the first stage, hydrological occurrences (hazards) are assessed and in the second step, flow and bridge scour variables are computed to represent the behavior of the river. The third stage evaluates the risk related to bridge scour by relating the relative scour depth to the infrastructure's priority factor and the last stage provides an approximate assessment of the risk rating of scour. Each stage is thoroughly described along with the initial data needed, the methodology used and the results. Based on the assessment of risk and level gathered following Highways Authority requirements, specific management measures were recommended. The Netaji Subhas bridge in India, which spans above the Gomati River, served as the testing ground for the suggested methodology.

The findings of the first step highlight the significance of taking model uncertainty at the time of design as well as the volatility of hydrological events into account. To define design floods, the modified arithmetic model averaging method is advised due to its capacity to manage model uncertainty. The HEC-RAS modeling tool was utilized to simulate different factors such as stream depth and velocity in the subsequent phase. The HEC-RAS scour module which accurately simulates the scour phenomena, was used to calculate the ultimate scouring depth. The model's strengths and weaknesses as well as the variables' calibration and validation, were highlighted. It was advised to go on to the bridge risk assessment after this practical evaluation of the overall scour depth as step 3.

A qualitative risk rating for the scour was assigned using the relative depth of scour and the priority factor of the Netaji Subhas bridge as measure. The bridge falls under risk category 5, indicating an acceptable risk level with no expected significant damages regardless of the flood return period. Although only one bridge was used to test this technology, the outcomes replicate that it can be used as the most susceptible pier on different bridges, independent of the shape of their foundations. To confirm the viability of the suggested technique for determining scour risk at bridge footings, additional case studies are advised. The calibration of the methods in the second step could be performed utilizing more complex CFD (Computational Fluid Dynamics) models; however, it is outside the scope of this work.

According to the authors, the above risk-based technique can be implemented in the general inspection of bridges and can be utilized to support decision-making in the face of uncertainty for bridges that are subject to unfavorable hydraulic condition.

Acknowledgement

The authors would like to thank to the Dean, FST and the Vice-Chancellor, ICFAI University, Tripura for providing necessary laboratory facilities and giving valuable guidance.

References

1. Akhlaghi E., Babarsad M.S., Derikvand E. and Abedini M., Assessment the effects of different parameters to rate scour around single piers and pile groups: a review, *Archives of Computational Methods in Engineering*, **27(1)**, 183-197 **(2020)**

2. Andrić J.M. and Lu D.G., Risk assessment of bridges under multiple hazards in operation period, *Safety Science*, **83**, 80-92 **(2016)**

3. Anees M.T., Abdullah K., Nawawi M.N.M., Ab Rahman N.N.N., Piah A.R.M., Zakaria N.A. and Omar A.M., Numerical modeling techniques for flood analysis, *Journal of African Earth Sciences*, **124**, 478-486 **(2016)**

4. Ang A.H., Structural risk analysis and reliability-based design, *Journal of the Structural Division*, **99(9)**, 1891-1910 **(1973)**

5. Argyroudis S.A. and Mitoulis S.A., Vulnerability of bridges to individual and multiple hazards-floods and earthquakes, *Reliability Engineering and System Safety*, **210**, 107564 **(2021)**

6. Barbetta S., Camici S. and Moramarco T., A reappraisal of bridge piers scour vulnerability: A case study in the Upper Tiber River basin (central Italy), *Journal of Flood Risk Management*, **10(3)**, 283-300 **(2017)**

7. Benkaci T., FFD 2.0., URL: https://ch.mathworks.com/matlabcentral/fileexchange/67367-flood-frequency-distribution-ffd-2-0; accessed: 2019-11-06 **(2019)**

8. Bento A.M., Gomes A., Viseu T., Couto L. and Pêgo J.P., Risk-based methodology for scour analysis at bridge foundations, *Engineering Structures*, **223**, 111115 **(2020)**

9. Beven K., How to make advances in hydrological modelling, *Hydrology Research*, **50(6)**, 1481-1494 **(2019)**

10. Beven K., Lamb R., Leedal D. and Hunter N., Communicating uncertainty in flood inundation mapping: a case study, *International Journal of River Basin Management*, **13(3)**, 285-295 **(2015)**

11. Bhattacharjee J., Choudhury P.R. and Devi L.S., Sediment yield of Gomati river catchment, Tripura, India using SWAT model, *Journal of Water and Land Development*, **30**, 67-76 **(2016)**

12. Bolduc L.C., Gardoni P. and Briaud J.L., Probability of exceedance estimates for scour depth around bridge piers, *Journal of Geotechnical and Geoenvironmental Engineering*, **134(2)**, 175-184 **(2008)**

13. Brandimarte L., Paron P. and Di Baldassarre G., Bridge pier scour: A review of processes, measurements and estimates, *Environmental Engineering and Management Journal*, **11(5)**, 975-989 **(2012)**

14. Briaud J.L., Gardoni P. and Yao C., Statistical, risk and reliability analyses of bridge scour, *Journal of Geotechnical and Geoenvironmental Engineering*, **140(2)**, 04013011 **(2014)**

15. Brunner G.W., HEC-RAS River analysis system hydraulic reference manual, Version 5.0 **(2016)**

16. Castellarin A., Kohnova S., Gaal L., Fleig A., Salinas J.L., Toumazis A. and Macdonald N., Review of applied-statistical methods for flood-frequency analysis in Europe, Izveštaj za COST Action ES0901, NERC/Centre for Ecology and Hydrology, 122 **(2012)**

17. Castiblanco M.E.M., Experimental study of local scour around complex bridge piers, Doctoral dissertation, Universidade do Porto (Portugal) **(2016)**

18. Central Water Commission, (n.d.), National Water Informatics Center, Retrieved from http://www.nicmar.cwc.gov.in/

19. Chen P., Huang Y., Mou J. and Van Gelder P.H.A.J.M., Probabilistic risk analysis for ship-ship collision: State-of-the-art, *Safety Science*, **117**, 108-122 **(2019)**

20. Chow V.T., Open-Channel Hydraulics McGraw-Hill Book Company, New York, 507-510 **(1959)**

21. Cunnane C., Statistical distribution for flood frequency analysis. WMO Operational Hydrology, Report No. 33, WMO-No. 718, Geneva, Switzerland **(1989)**

22. Dey S., Fluvial hydrodynamics (Vol. **818**), Berlin: Springer **(2014)**

23. Di Baldassarre G., Schumann G., Bates P.D., Freer J.E. and Beven K.J., Flood-plain mapping: a critical discussion of deterministic and probabilistic approaches, *Hydrological Sciences Journal–Journal des Sciences Hydrologiques*, **55(3)**, 364-376 **(2010)**

24. Ettema R., Constantinescu G. and Melville B.W., Flow-field complexity and design estimation of pier-scour depth: Sixty years since Laursen and Toch, *Journal of Hydraulic Engineering*, **143(9)**, 03117006 **(2017)**

25. Farrar C.R. and Jauregui D.A., Comparative study of damage identification algorithms applied to a bridge: I. Experiment, *Smart Materials and Structures*, **7(5),** 704 **(1998)**

26. Garg R.K., Chandra S. and Kumar A., Analysis of bridge failures in India from 1977 to 2017, *Structure and Infrastructure Engineering*, **18(3)**, 295-312 **(2022)**

27. Government of Tripura, Gomati River Basin Management Plan, Retrieved from https://www.tripura.gov.in/sites/default/files/Gomati%20River%20Basin%20Management%20Plan_0.pdf **(2018)**

28. Haimes Y.Y., Kaplan S. and Lambert J.H., Risk filtering, ranking and management framework using hierarchical holographic modelling, *Risk Analysis*, **22(2)**, 383-397 **(2002)**

29. Hamidifar H., Zanganeh-Inaloo F. and Carnacina I., Hybrid scour depth prediction equations for reliable design of bridge piers, *Water*, **13(15)**, 2019 **(2021)**

30. Highways Agency, The assessment of scour and other hydraulic actions at highway structures, *Tech. Rep*., **3(4)**, The Stationery Office London, UK **(2012)**

31. Hoeting J.A., Madigan D., Raftery A.E. and Volinsky C.T., Bayesian model averaging: a tutorial (with comments by M. Clyde, David Draper and EI George and a rejoinder by the authors, *Statistical science*, **14(4)**, 382-417 **(1999)**

32. Horritt M.S. and Bates P.D., Evaluation of 1D and 2D numerical models for predicting river flood inundation, *Journal of Hydrology*, **268(1-4),** 87-99 **(2002)**

33. Johnson P.A. and Jones J.S., Merging laboratory and field data in bridge scour, *Journal of Hydraulic Engineering*, **119(10)**, 1176-1181 **(1993)**

34. Johnson P.A., Clopper P.E., Zevenbergen L.W. and Lagasse P.F., Quantifying uncertainty and reliability in bridge scour estimations, *Journal of Hydraulic Engineering*, **141(7)**, 04015013 **(2015)**

35. Kabili Salma, Algouti Ahmed, Algouti Abdellah and El Ghouat Akram, Quantification of water erosion using empirical models RUSLE and EPM in the Rheraya basin in the High Atlas of Marrakech, *Disaster Advances*, **16(5),** 19-28 **(2023)**

36. Klemeš V., Tall tales about tails of hydrological distributions. II, *Journal of Hydrologic Engineering*, **5(3)**, 232-239 **(2000)**

37. Laursen E.M., Scour at bridge crossings, *Journal of the Hydraulics Division*, **86(2)**, 39-54 **(1960)**

38. Laursen E.M., An analysis of relief bridge scour, *Journal of the Hydraulics Division*, **89(3)**, 93-118 **(1963)**

39. Lee S.O., Abid I. and Hong S.H., Effect of complex shape of pier foundation exposure on time development of scour, *Environmental Fluid Mechanics*, **21**, 103-127 **(2021)**

40. McMillan H.K., Westerberg I.K. and Krueger T., Hydrological data uncertainty and its implications, *Wiley Interdisciplinary Reviews: Water*, **5(6)**, e1319 **(2018)**

41. McKay S.K. and Fischenich J.C., Robust prediction of hydraulic roughness, Engineer Research and Development Center Vicksburg MS Coastal and Hydraulics Lab **(2011)**

42. Melville B. and Coleman S., Bridge scour Water **(2000)**

43. Menzies J.B., Bridge failures, hazards and societal risk, In Safety of bridges, Thomas Telford Publishing, 36-41 **(2011)**

44. Miner N. and Alipour A., Bridge Damage, Repair Costs and Fragilities for Inland Flood Events, *Journal of Bridge Engineering*, **27(8)**, 04022057 **(2022)**

45. Mohammadpour R., Ghani A.A., Vakili M. and Sabzevari T., Prediction of temporal scour hazard at bridge abutment, *Natural Hazards*, **80**, 1891-1911 **(2016)**

46. Montalvo C., Cook W. and Keeney T., Retrospective analysis of hydraulic bridge collapse, *Journal of Performance of Constructed Facilities*, **34(1)**, 04019111 **(2020)**

47. Moran P.A.P., The statistical treatment of flood flows, *Eos, Transactions American Geophysical Union*, **38(4)**, 519-523 **(1957)**

48. Naghettini M. and Pinto É.J.D.A., Hidrologia estatística, CPRM **(2007)**

49. Okoli K., Breinl K., Brandimarte L., Botto A., Volpi E. and Di Baldassarre G., Model averaging versus model selection: estimating design floods with uncertain river flow data, *Hydrological Sciences Journal*, **63(13-14),** 1913-1926 **(2018)**

50. Okoli K., Mazzoleni M., Breinl K. and Di Baldassarre G., A systematic comparison of statistical and hydrological methods for design flood estimation, *Hydrology Research*, **50(6)**, 1665-1678 **(2019)**

51. Ramesh A., Response of Flood Events to Land Use and Climate Change: Analyzed by Hydrological and Statistical Modeling in Barcelonnette, France, Springer Science and Business Media **(2012)**

52. Ramesh R., Datta B., Bhallamudi S.M. and Narayana A., Optimal estimation of roughness in open-channel flows, *Journal of Hydraulic Engineering*, **126(4)**, 299-303 **(2000)**

53. Raus and M. and Haugen S., Risk assessment: Theory, methods and applications, Wiley series in statistics in practice; 2nd edition, Hoboken, NJ: John Wiley and Sons **(2020)**

54. Richardson E.V. and Davis S.R., Evaluating scour at bridges (No. FHWA-NHI-01-001), United States, Federal Highway Administration, Office of Bridge Technology **(2001)**

55. Roca M. and Whitehouse R.J.S., Scour risk assessment at river crossings **(2012)**

56. Shahriar A.R., Ortiz A.C., Montoya B.M. and Gabr M.A., Bridge Pier Scour: An overview of factors affecting the phenomenon and comparative evaluation of selected models, *Transportation Geotechnics*, **28**, 100549 **(2021)**

57. Sheppard D.M. and Renna R., Bridge scour manual, 605 Suwannee Street, Tallahassee, FL, 32399-0450 **(2010)**

58. Sturm T. et al, Combining individual scour components to determine total scour, Transport Res Board **(2018)**

59. Te Chow V., Maidment D.R. and Mays L.W., Applied hydrology **(1988)**

60. Todinov M., Reliability and risk models: setting reliability requirements, John Wiley and Sons **(2015)**

61. Ul Hassan M., Hayat O. and Noreen Z., Selecting the best probability distribution for at-site flood frequency analysis; a study of Torne River, *SN Applied Sciences*, **1**, 1-10 **(2019)**

62. Wang C., Yu X. and Liang F., A review of bridge scour: mechanism, estimation, monitoring and countermeasures, *Natural Hazards*, **87**, 1881-1906 **(2017)**

63. Washer G., Connor R., Ciolko A., Fish P., Kogler R., Forsyth D. and Nasrollahi M., Inspection Planning Based on Risk Analysis, In Structures Congress, 699-710 **(2014)**

64. Wardhana K. and Hadipriono F.C., Analysis of recent bridge failures in the United States, *Journal of Performance of Constructed Facilities*, **17(3)**, 144-150 **(2003)**

65. Yan H. and Moradkhani H., Bayesian model averaging for flood frequency analysis, In World Environmental and Water Resources Congress 2014, 1886-1895 **(2014)**

66. Yang Y., Melville B.W., Macky G.H. and Shamseldin A.Y., Local scour at complex bridge piers in close proximity under clear-water and live-bed flow regime, *Water*, **11(8)**, 1530 **(2019)**

67. Yilmaz T., Risk assessment of highway bridges under multi-hazard effect of flood induced scour and earthquake, The Pennsylvania State University **(2015)**

68. Zaifoglu H. and Imam B., Effect of model data availability on scour risk of bridges, *Natural Hazards*, **114(3)**, 3445-3469 **(2022)**

69. Zheng W. and Yu W., Probabilistic approach to assessing scoured bridge performance and associated uncertainties based on vibration measurements, *Journal of Bridge Engineering*, **20(6)**, 04014089 **(2015)**.

(Received 15th October 2023, accepted 16th December 2023)

*****