Journal of Civil and Hydraulic Engineering
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Comparative Analysis of 1D and 2D Modeling Approaches for Scour Depth Estimation: A Case Study of the Kelanisiri Bridge, Sri Lanka

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Received: 06-20-2024 **Revised:** 09-10-2024 **Accepted:** 09-20-2024

Citation: A. Thembiliyagoda, K. De Silva, and N. Wijayaratna, "Comparative analysis of 1D and 2D modeling approaches for scour depth estimation: A case study of the Kelanisiri Bridge, Sri Lanka," *J. Civ. Hydraul. Eng.*, vol. 2, no. 3, pp. 171–184, 2024. https://doi.org/10.56578/jche020304.

Abstract: The scouring process, characterised by the erosion of sediment around bridge piers due to fluid flow, poses a significant risk to the structural integrity of bridges. Scour depth, defined as the vertical distance from the initial riverbed level to the bottom of the scour hole, is driven by the formation of vortices near bridge piers. Mitigating scour damage after it has advanced to a critical stage is often more disruptive and costly than preemptive measures based on accurate predictions. In response to this challenge, a range of one-dimensional (1D) and two-dimensional (2D) numerical modelling techniques has been developed for scour depth estimation around bridge piers. Among the available methods, the Hydrologic Engineering Center's River Analysis System (HEC-RAS) is widely employed, with the majority of studies focusing on the 1D modelling approach. The current study evaluates the relative efficacy of 1D and 2D models using the case of the Kelanisiri Bridge, which traverses the Kelani River in Sri Lanka. The performance of the 1D model was assessed by comparing predicted water levels at an intermediate river gauge with field data, while the 2D model was calibrated and validated against observed riverbed levels. Both approaches were applied to estimate scour depths following the 2016 flood event. The findings revealed that the 2D HEC-RAS model provided a superior match with observed field data when compared to the 1D model, achieving a coefficient of determination (R^2) of 0.98 and a root mean square error (RMSE) of 0.13, indicating a higher degree of accuracy and reliability. As a result, the 2D model is recommended as the more effective approach for predicting scour depth around bridge piers. Further validation of these numerical results through scaled laboratory physical modelling is recommended to ensure greater accuracy in future predictive efforts.

Keywords: Numerical simulation; Pier scour; Model validation; Hydrologic Engineering Center's River Analysis System (HEC-RAS); Flood modelling

1 Introduction

Lowering of the level of the riverbed due to erosion is termed scouring. The depth of scour refers to the extent to which the riverbed lowers below its original level [1]. Scouring tends to occur around bridge abutments and piers, causing considerable harm to the integrity of the structures. The cause for this issue is the disturbance caused to the river flow by the piers and abutments of a bridge structure. Scouring action amends the flow pattern around the piers and abutments, leading to an increase in shear stress. The damage due to scour can lead to the failure of the bridge structures. In general, the design event for a scour analysis is usually the 100-year event.

Bridge piers provide vertical support for the bridge deck and mainly transfer the vertical superstructure loads to the foundations. Since the piers are directly related to the river flow, the riverbed around the pier also encounters scouring caused by the flow. The sediment transport is a function of flow, and accordingly, the transport capacity of the flow gets modified when the river flow comes across a bridge pier. A propensity for the development of scour holes arises in areas where the capacity for transport of sediments out of the area surpasses the rate at which material is supplied to the area [1].

Pier scouring is an imperative factor in bridge hydraulic design. However, measuring the bridge's pier scour in the field, particularly during the flood season, is difficult. Scour, being a complex and intriguing problem involving certain interactions, has led to a vast amount of research. Recent research has highlighted the use of diverse models to simulate the scouring effect around bridge piers. Since the riverbed around a pier is lowered during the scouring action, there exists a tendency to expose the foundation of the pier, causing a risk to the stability of the structure. Furthermore, a numerical model that could reproduce the scouring effect around bridge piers is an indispensable fact considering the safety and integrity of the bridge structures since implementation of preventive measures based on the scour depths predicted by the model is more cost-effective and less disruptive.

The total depth of the scour hole around a pier is the change in the riverbed elevation around the pier forming a hole (Figure 1). When the river flow is obstructed by a pier, the flow characteristics around these structures change. The formation of a scour hole occurs when the river flow is obstructed by bridge piers. As the incoming flow strikes the bridge structure, horseshoe vortices form in front of the piers, and the magnitude of these vortices decreases with increasing flow depth. The changed flow pattern and the strengthened hydrodynamic forces drive the sediment movement, forming scour holes around the bridge piers. The intensity of scouring depends on factors such as flow intensity, flow shallowness, pier shape, sediment coarseness, and more [2]. At the initiation, the scour zones develop and extend back around the face of the pier. Consequently, a groove is eroded adjacent to the front of the pier, with the cause being the downflow at the pier face impinging on the erodible bed [3]. The process of formation of scour holes is primarily complex due to the interaction between the three-dimensional flow patterns and the riverbed materials [4]. The formation of the scour hole initiates when the transport rate of sediments away from the base region is greater than the transport rate into the region. The strength of the horseshoe vortex diminishes with the increase in the scour hole depth and thus the rate of sediment transport from the base region. Wake vortex refers to the vertical vortices that develop on the downstream side of the pier. Both the horseshoe and wake vortices remove sediment from the pier base region.

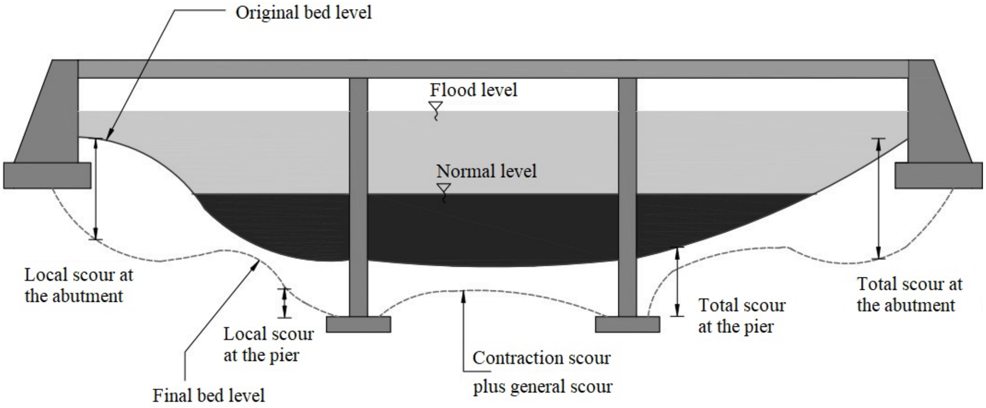

Figure 1. Types of scour around a bridge pier [5]

Dey et al. [5] had presented a kinematic model considering horseshoe vortex (HSV) motion in the scour hole. In their study, the upstream section of the pier had been divided into two zones: zone 1 (vertically upward from the inclined bed) and zone 2 (vertically upward from the planner bed and close to the pier). Based on velocity component distribution patterns, a three-dimensional kinematic model was developed to describe vortex flow around circular piers within a quasi-equilibrium scour hole under clear water conditions. The results obtained from the above model had been satisfactory in comparison with the observations made Melville and Chiew [6]. Khosronejad et al. [7] performed a simulation using numerical modeling to analyze the scouring effect around bridge piers. The hydrodynamic model employed successfully handled unsteady Reynolds averaged Navier Stokes conditions, utilizing the $\mathrm{k}-\omega$ turbulence model and employing a second-order accurate fractional method. The impact of grid resolution on the predictive power of the model had been analyzed using a grid sensitivity survey [7]. Further, the literature demonstrates the application of computational studies for unsteady Reynolds-averaged Navier-Stokes (URANS) models by focusing on flow patterns around piers on a flat, rigid bed. It had also been found that the two-equation isotropic eddy viscosity turbulence models, which are commonly used to solve the URANS equations, tend to overestimate the magnitude of eddy viscosity at the junction between the bridge foundation and the bed. This overestimation can suppress and significantly underestimate the intensity of the THSV system, which is crucial for the initiation of scour [8–10]. Mia and Nago [11] had assessed the evolution of bed shear stress around the pier integrated along with the bed load sediment transport theory and suggested a method for the computation of scour depth differing with time. They had observed that in the equilibrium state of scour for a given sediment size, the flow around the pier is unable to move any additional sediments from the scour hole.

When scour depth is estimated using laboratory flume setups, numerical simulations can be more cost-effective and provide a better understanding of the relevant flow and transport phenomena [12]. Software such as flo2dh, FLUENT, HEC-RAS, and SSIM is available to record the scouring process around bridge piers. Among these are the sediment transport equations, flow pattern analysis in detail, complicated river geometry modeling capability, and an array of analysis tools offered by the HEC-RAS software. Additionally, research indicates that 2D models provide more accurate scour depth estimates compared to 1D models [4, 13, 14].

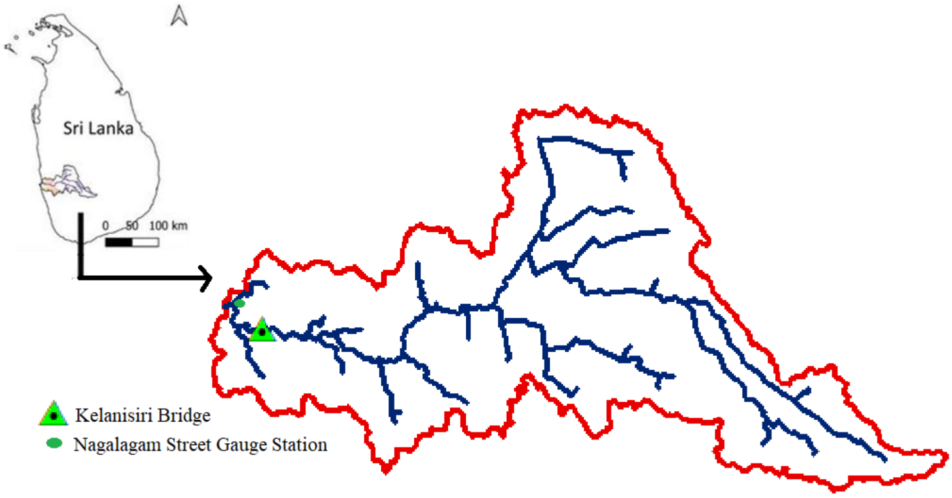

Figure 2. Location map of Kelanisiri bridge in the Kelani river basin

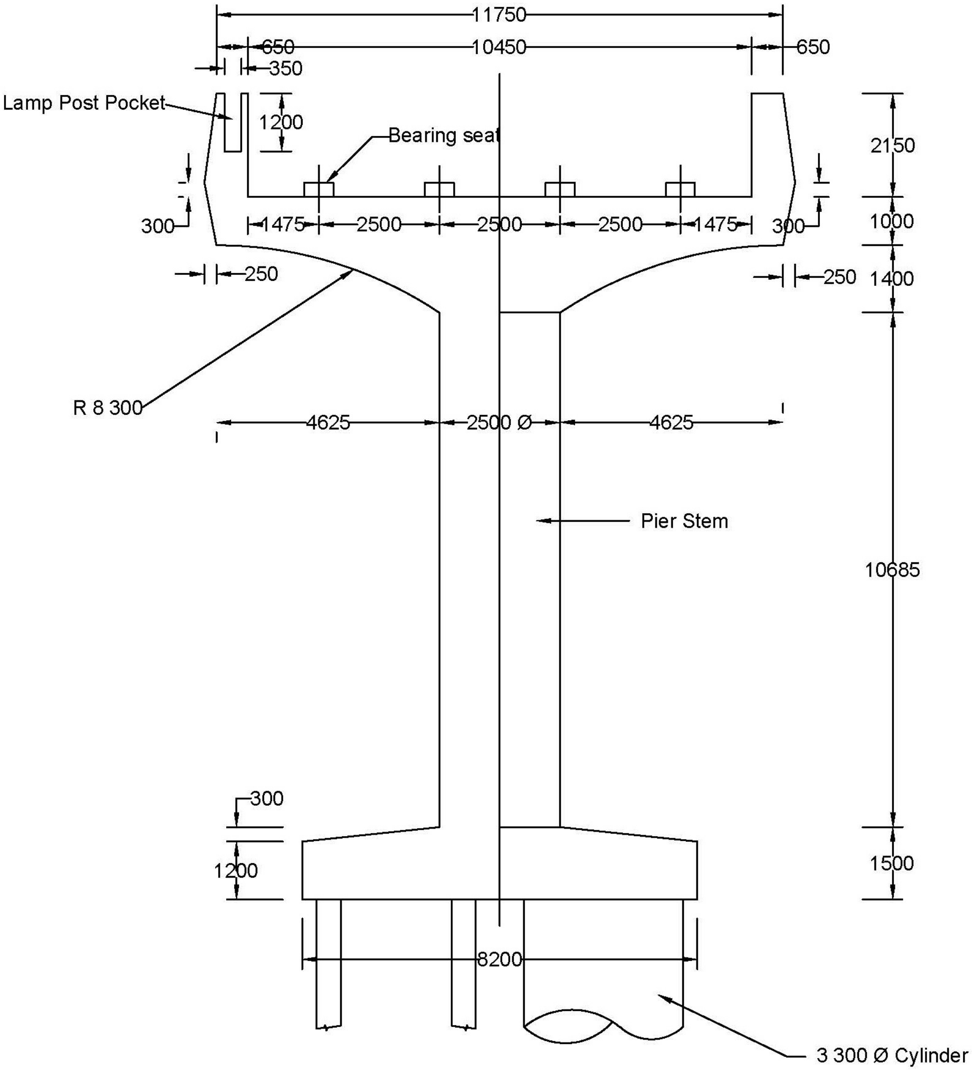

Figure 3. Kelanisiri bridge pier sketch (dimensions in mm)

Simulating the depth of scour using HEC-RAS software in a 1D approach is supported by literature [15]. Noor et al. [15] had adopted HEC-RAS simulation to simulate the scouring phenomenon surrounding the bridge piers. The outcomes were then compared to those obtained from the physical model. Yu and Yu [4] had conducted a comparative study on 1D and 2D hydraulic simulations for bridge scour prediction with the incorporation of HEC-RAS and Flo2dh approaches for the 1D and 2D simulations, respectively. Flo2dh 2D results had outperformed the HEC-RAS 1D simulation. With the advancement of the software, the scouring phenomenon can be simulated in a 2D approach as well. Research exploring the application of HEC-RAS 2D numerical models for simulating scour depth is infrequently encountered. This study includes a comparative analysis of the HEC-RAS 1D and 2D modeling approaches to estimate scour depth around bridge piers. The comparison is based on results from a case study conducted at Kelanisiri Bridge, located across the Kelani River in Sri Lanka (6°56'58.54"N, 79°55'13.11"E). The Kelani river basin is the second-largest in Sri Lanka (Figure 2), with approximately 14 bridges spanning its width. The Kelanisiri bridge, chosen for its availability of relevant data, features a span of 134 meters and a width of 10.4 meters. It is supported by two cylindrical piers that are susceptible to scouring threats (Figure 3).

2 1D Numerical Model for the Scour Depth Estimation

2.1 1D Model Development

At the initial stage, a protracted literature study was conducted to identify the most feasible method for the prediction of pier scour depth using a numerical approach. Table 1 depicts a summary of some prevailing software for modeling the scouring effect. Based on the comparison of available software, the HEC-RAS modeling approach was utilized for the simulation.

Table 1. Comparison of software available for modeling

Software	Features	Pros	Limitations	Source
SSIIM	The SSIIM program solves the Navier-Stokes equations of three-dimensions and general non-orthogonal.	Ability to analyze complex geometries to model sediment transport in a live bed.	Need highly ac-curate data for the computations. The size and alignment of the cells will strongly influence accuracy, convergence, and computational time.	[16, 17]
Flow 3D	Offers a powerful capacity to examine the manner in which gases and liquids move, allowing the solution of transient problems, free surface modeling, and the assessment of sediment transport.	Ideal for simulating local scour over short epidemic time scales. Provides the flexibility and utility for porous media flow, as well as easy setup for complex structures.	Excessive computational time is required.	[18]
Flo2DH	The FESWMS Flo2DH model simulates flow in two dimensions in the horizontal plane. It uses a finite element mesh and the Galerkin finite element method of solving three partial differential equations representing the conservation of mass and momentum.	Can simulate the movement of water and non-cohesive sediment in rivers.	More complex and difficult to set up.	[19]
HEC-RAS	Capable of computing the contraction scour, local scour at piers and abutments, and the total scour depths inside the bridge. The 2D flow routing capabilities in HECRAS have been developed for the performance of 2D or combined 1D/2D modeling.	Open-source software.	Users may find numerical instability problems during unsteady analyses, especially in steep and/or highly dynamic rivers and streams.	[20, 21]

The scour depth estimation under most of the 1D approaches is governed by empirical equations. A literature review by McIntosh found that more than 35 equations had been proposed for predicting the depth of scour at a bridge pier [22]. Most published scour prediction methodologies/equations, of which there are many, are empirical and, for the most part, based on laboratory-scale data. A consequential scatter can be noticed in the published historical data due to diversified reasons which include tests performed for insufficient durations, inadequate or insufficient instrumentation used, important parameters not being measured, etc. [23].

Since the number of structures, sediment, and flow parameters that influence scour depth are large and, for practical reasons, must be limited to those with the greatest impact when developing a predictive method. This matter has resulted in different dimensionless groups of parameters being used, depending on the developer's understanding on which parameters are of uttermost importance. This is because the scouring effect is a very complex phenomenon that results from the interaction between the flow around a bridge pier and the erodible bed surrounding it [24]. It is inevitable that since many pier-scour equations are based on data from laboratory flumes and from cohesionless silt- and sand-bottomed streams, they tend to overestimate scour for piers specially located on coarse-bed materials.

Validation of the scour formulae is vital for the identification of the uncertainties associated. Mohamed et al. [24] and Zevenbergen [25] had tested the 4 most commonly used scour depth identification equations to determine their accuracy. The equations and the models validated were the Colorado State University equation (CSU), Melville and Sutherland equation (M&S), Jain and Fisher equation (J&F), and Lauren and Toch equation (L&T). Statistical tests had been conducted to evaluate the accuracy of the prediction obtained from the four formulae and models used in estimating scour depth at the bridge pier. Results are summarized in Table 2.

Table 2. Comparison of computed scour depth using empirical equations and observed scour depth

Year	**Bridge Location**	**Q (m^3/s)**	**Pier Width (b) m**	**Observed Scour Depth (m)**	**Scour Applying CSU Formula (m)**	**Scour Applying M&S Formula (m)**	**Scour Applying J&F Formula (m)**	**Scour Applying L&T Formula (m)**
1948	Pakistan	2437	3.05	11.24	8.75	11.58	10.41	9.88
1949	Pakistan	1474	3.05	8.8	8.36	11.17	10.03	9.48
1950	Pakistan	5469	3.05	12.44	11.71	14.67	13.38	12.88
1951	Pakistan	1247	3.05	9.2	8.24	11.02	9.88	9.34
1952	Pakistan	1587	3.05	9.76	8.21	11.02	9.89	9.34
1953	Pakistan	2352	3.05	11.42	8.99	11.83	10.67	10.12
1954	Pakistan	4874	3.05	11.22	11.04	13.98	12.72	12.21
1962	Canada	567	1.83	9.76	9.83	11.44	11.26	10.75
1962	Canada	510	1.52	8.54	8.46	9.77	9.69	9.24
1970	India	3364	9.15	13.87	13.2	20.44	17.13	16.01

The validation process and the statistical tests had depicted that the Colorado State University Formula is the best among the four selected formulae, followed by Laursen and Toch, Jain and Fisher and Melville and Sutherland formulae [24]. It was noted that the scour depths predicted for various flows by the Colorado State University formula had scattered around the line of perfect agreement, while the predicted values by other formulae clearly over predicted. Zevenbergen [25] had identified that the HEC-18 equation is considered to be the most empirical because it is a regression fit of lab data with several “correction” factors that have been added over time. Apart from this the Froehlich’s equation too had fitted to 83 measurements from bridges onsite in US and elsewhere [26]. Ranking the performance of scour-prediction equations is difficult because of the tradeoff between accuracy and underpredictions. If only accuracy is considered, the sum of squared errors can be used to evaluate the equations’ performance.

Improvements to the equations are still being made, with the ultimate goal of decreasing scour underestimation and overestimation. During heavy floods, scour depths assumed in the bridge design could be surpassed if pier scour is underestimated. Excessive scour could undermine the bridge by reducing support for the bridge pier. Some empirical formulae have been changed to generate more cautious scour predictions to guarantee that pier-scour depth is not underestimated [27]. Accordingly, the adaptation of a suitable numerical simulation method is certainly vital for the prediction of scour depths.

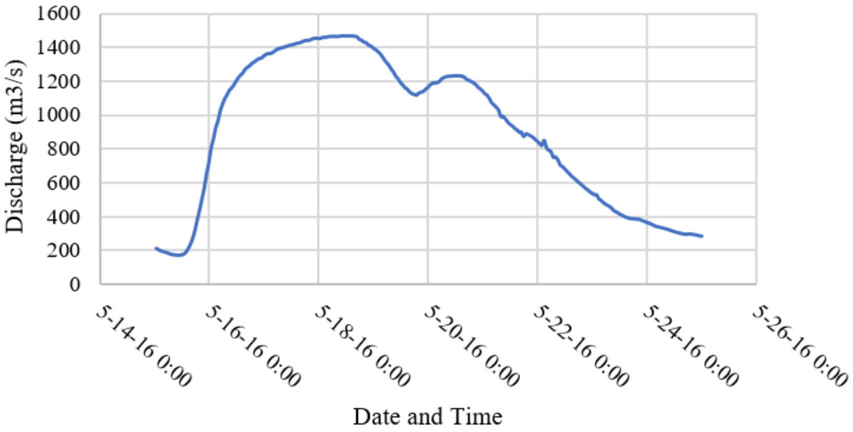

Figure 4. Flow hydrograph (2016 flood)-Upstream boundary condition

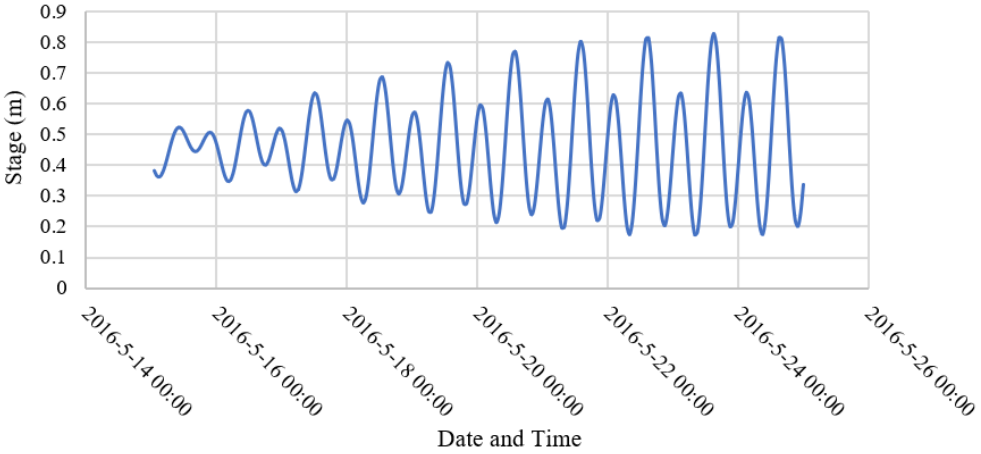

Figure 5. Stage hydrograph (2016 flood)-Downstream boundary condition

The 1D scour simulation is the most widely adopted application of HEC-RAS scour modeling. 1D model comprises river cross-section data depicting the river stations along the considered stretch. The cross-section data were interpolated at 20 m intervals to depict the river geometry at the bridge site. Upon the development of the geometry data, the bridge station was identified and bridge geometry data pertaining to the selected bridge were utilized to incorporate the bridge structure data into the model. Unsteady flow simulation was performed for the period between the years 2003 to 2016, ahead of the scour depth calculation Flow rates recorded at Hanwella gauge station and tidal values at sea outfall were utilized respectively as the upstream and downstream boundary conditions for the model (Figure 4 and Figure 5). Subsequent to unsteady flow analysis, the scour depth calculation was performed using the governing empirical formulae.

Contraction scour and local scour can be analyzed individually using the model [28] Before predicting the contraction scour, the conditions of live-bed or clear-water at the bridge site were determined by comparing the critical velocity of the bed material (Vc) with the mean flow velocity (V). The critical velocity of the bed material (V_c) was calculated as follows [29].

$$V_c = K_u y_1^{1/6} D_{50}^{1/3} \tag{1}$$

where, V_c=Critical velocity above which material of size D_{50} and smaller will be transported, (ft/s or m/s), y_1=Average depth of flow in the main channel or overbank area at the approach section, (ft or m) and, D_{50}=Bed material particle size in a mixture of which 50% are smaller, (ft or m).

The HEC-18 pier scour equation (based on the Colorado State University (CSU) equation) is recommended for both live bed and clear-water pier scour determination and the equation is as follows [30].

$$y_s = 2.0 K_1 K_2 K_3 K_4 a^{0.65} y_1^{0.35} Fr_1^{0.43} \tag{2}$$

where,

y_s=Depth of scour in (ft or m)
K_1=Correction factor for the pier nose shape
K_2=Correction factor for the angle of attack of flow
K_3=Correction factor for bed condition
K_4=Correction factor for armoring of bed material
a=pier width (ft or m)
y_1=Flow depth directly upstream of the pier (ft or m)
Fr_1=Froude number directly upstream of the pier

The equation predicts maximum pier scour depths. The CSU equation and the Froehlich equation are available for the estimation of scour depth around bridge piers. Further, it has been observed that the Froehlich method is not as sensitive as the CSU method to an increase in discharge when calculating scour depth [31]. Furthermore, the sediment model should not be used to calculate the scour depth around bridge piers or abutments because the software's 1D mobile bed sediment transport features rely on reach scale capabilities. The contraction scour depth surrounding the bridge piers and the local scour depth are determined independently by the bridge scour depth calculation platform. The estimation of contraction scour was carried out using a modified version of Laursen's

(1960) live bed scour equation.

$$y_2 = y_1 \left[\frac{Q_2}{Q_1}\right]^{6/7} \left[\frac{W_1}{W_2}\right]^{k_1} \tag{3}$$

$$y_s = y_2 - y_0 \tag{4}$$

where,

y_s=Average depth of contraction scour (ft or m)
y_2=Average depth after scour in the contracted section (ft or m)
y_1=Average depth in the main channel at the approach section (ft or m)
y_0=Average depth in the main channel at the contracted section before scour (ft or m)
Q_1=Flow in the main channel at the approach section, which is transporting sediments (cfs or m^3/s)
Q_2=Flow in the main channel at the contracted section which is transporting sediments (cfs or m^3/s)
W_1=Bottom width in the main channel at the approach section, (ft or m)
This is approximated as the top width of active flow area in HEC-RAS
W_2=Bottom width of the main channel at the contracted section less pier widths, (ft or m)
This is approximated as the top width of active flow area in HEC-RAS
k_1=Exponent for the mode of bed material transport

2.2 Model Results

The results obtained from the unsteady flow simulation were compared with the observed data by considering the water levels at Nagalgam Street gauge station, which is an intermediate station along the considered river stretch (Figure 6). Following the comparison, the scour depths were obtained using the hydraulic design platform.

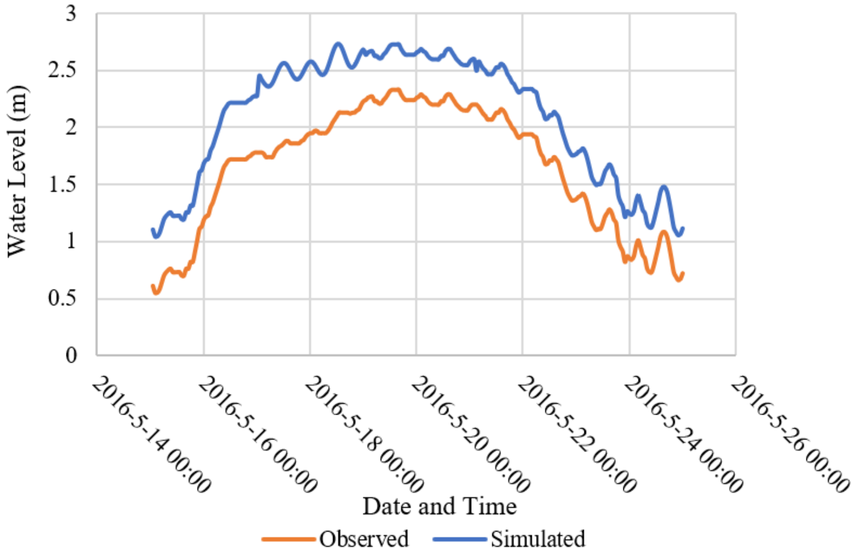

Figure 6. Comparison of 1D model simulated results with observed data

Table 3. Scour depth simulation results (1D model)

Type of Scour	Pier 1	Pier 2
Local scour	1.8 m	2.5 m
Contraction scour	0.7 m	0.6 m
Total scour	2.5 m	3.1 m

The scour depth computed using the CSU equation and Froehlich equation accounts for the depth of the scour hole formed due to local scour around the bridge piers. In addition to local scour, the contribution of contraction scour to the formation of scour holes was calculated separately using a different set of empirical equations. The necessary parameters for the empirical equation were fed into the model. The hydraulic analysis at the upstream cross-section of the bridge revealed a maximum water depth of 2.3 m and a velocity of 1.45 m/s. The depth of the scour holes after the 2016 flood event were obtained as per Table 3 at the end of the simulation.

3 2D Numerical Model for Scour Depth Estimation

3.1 2D Hydraulic Model Development

The 2D modeling method used by HEC-RAS is drastically different from the 1D modeling approach. 2D modeling consists of a hydraulic model combined with a sediment transport model. This method does not include any of the empirical equations for the direct estimation of scour depth. One solution scheme used in HEC-RAS 2D modeling is finite volume. Three-dimensional fluid motion is described by the Navier-Stokes equations. In order to simulate the flow patterns and depict the spatial distribution of water, the 2D model makes use of a mesh of connected cells. The model computes water surface elevations and velocities throughout the domain using equations based on the principles of mass and momentum conservation. These principles are fundamental to 2D hydraulic models.

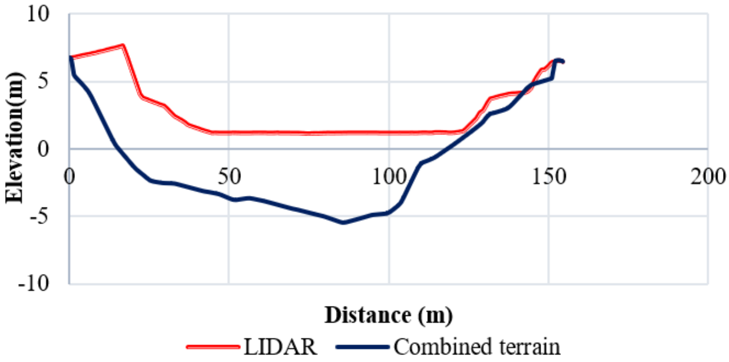

Figure 7. River bathymetry comparison at the bridge site

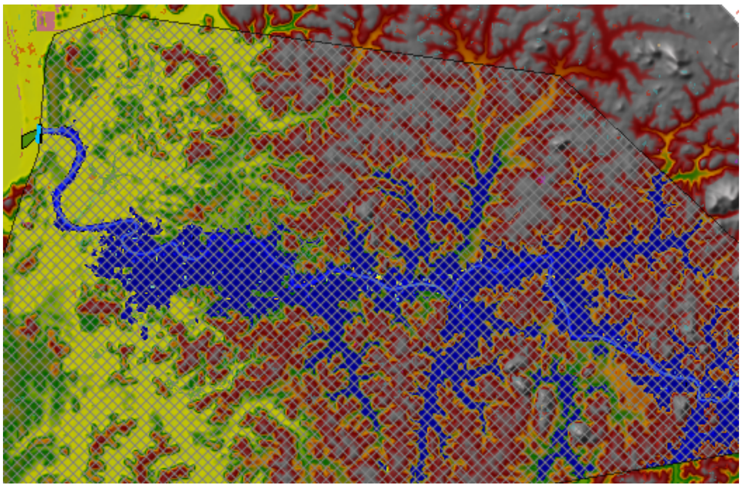

Figure 8. HEC-RAS 2D computational mesh

The river cross-section data from a 2003 survey were incorporated into the model and interpolated at 20-meter intervals. The geotiff generated using cross-section data was then merged with LIDAR data to enhance the accuracy of the terrain profile for the selected river segment (Figure 7). A 2D mesh was developed with a coarse cell resolution of 50 m x 50 m and a fine cell resolution of 5 m × 5 m for the channel (Figure 8). The mesh was enhanced along the channel, and the bridge piers were integrated into the terrain by modifying a duplicate of the original terrain. The time step was decided according to the Courant number, which is essential for maintaining simulation stability and accuracy in HEC-RAS. This number connects the size of computational grid cells to the time step, resulting in the selection of a 60-second time step for the simulation.

Additionally, the 2D model required the incorporation of land use data. The Kelani river basin is experiencing significant commercialization, posing prominent water quality and environmental challenges in Sri Lanka, including bio diversity loss [32]. The lower Kelani basin is densely urbanized, while the upper basin remains predominantly green. Recommendations of Chow [33] were followed in designating Manning's roughness coefficient. The boundary condition on the upstream side was set using the hourly flow hydrograph at Hanwella (Figure 4) while the lower boundary condition was based on the hourly tidal fluctuations at Sea Outfall (Figure 5). As a result, the hydrograph at Nagalagam Street successfully replicated tidal variations, including backwater effects [34]. The 2D hydraulic model was calibrated with the 2016 flood event and validated with the 2018 flood event (Figures 9 and 10). Model calibration involved adjusting Manning's coefficient, ultimately adopting a value of 0.35 for the river channel.

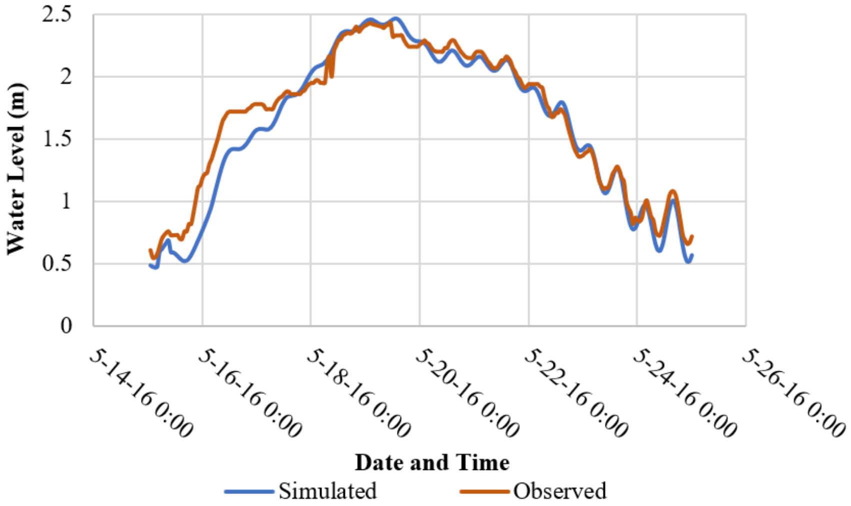

Figure 9. Comparison of stages at Nagalagam Street gauge station for the 2016 flood (2D model-Calibration)

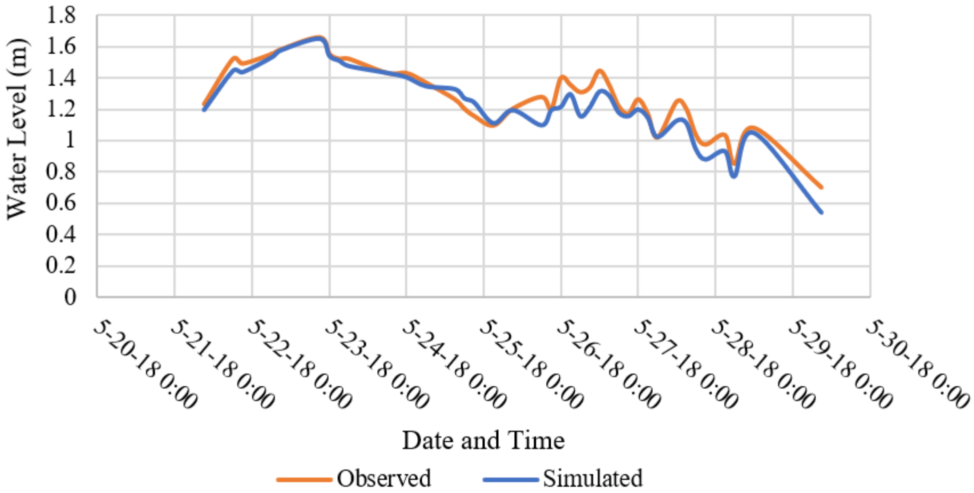

Figure 10. Comparison of stages at Nagalagam Street gauge station for the 2018 flood (2D model-Validation)

3.2 2D Sediment Model Development

Since shallow water equations perform better than diffusion wave equations with 2D models, shallow water equations were chosen for the simulation. A sediment data file was included in the developed model to combine the hydraulic model with a sediment model. Constructing a well-defined hydraulic geometry is crucial for a reliable sediment model. A similar study [35] assessed scour depth around an abutment and found that using four times D50 as the roughness value provided the best agreement with experimental results.

Sediment transport functions simulate non-linear transport processes. Model results tend to be very sensitive to the selected function. The Ackers and White equation is suitable for non-cohesive sediments and a wide range of flow conditions, whereas the Engelund and Hansen equation is applicable for fine sands and silts. The Laursen-Copeland formula was not selected since the formula is developed primarily for uniform flow conditions and is less accurate in non-uniform flows. The Meyer-Peter and Muller equation was not selected since it does not account for suspended load and may be less accurate for finer sediments. Even though the Toffaleti equation is suitable for rivers with significant suspended loads, particularly in large rivers, this method was also not selected due to its complex and data-intensive nature. Further, the Wu method was also rejected since it's relatively new compared to other methods and requires more validation in different environments [36]. Accordingly, following a thorough comparison between the available various methods, the Van Rijn sediment transport formula was selected, and it showed a strong correlation between simulated and observed bed changes.

Riverbed gradation is a major segment in sediment models. The HEC-RAS 2D model features a platform with a bed gradation template. Particle size analysis was conducted on riverbed samples collected from various locations within the selected river stretch to analyze the particle size distribution of the riverbed material, and a composition rich in quartz, biotite, feldspar, garnet, and sapphire was identified. The minerals biotite and garnet are abundant in smaller particle sizes such as 0.106 mm, 0.053 mm, and 0.047 mm [34]. The significant presence of quartz in the Kelani River indicates it has been transported over long distances from its origin.

Choosing an advection-diffusion parameter is essential when developing a 2D sediment transport model. The bed sorting or armoring method, which traces bed gradation to compute grain class-specific transport capacities, was used. Since the model is 2D, the active layer sorting method was adopted, and the free particle settling speed was calculated using the fall velocity formula.

Similar to the hydraulic model, the sediment model also requires an upstream boundary condition. For this model, the rating curve boundary condition was used as the influx sediment boundary condition. According to Mallawatantri et al. [37], the average amount of sediment composition in the main Kelani River is about 2,350 t/ha/yr at a river location corresponding to a drainage area of 175,000 ha, which drains about 75% of the total basin area. This indicates a sediment yield of approximately 0.134 t per ha per annum. Field observations by Mallawatantri et al. [37], including the total sediment load passing at Hanwella Bridge, were used to develop the rating curve (Figure 11).

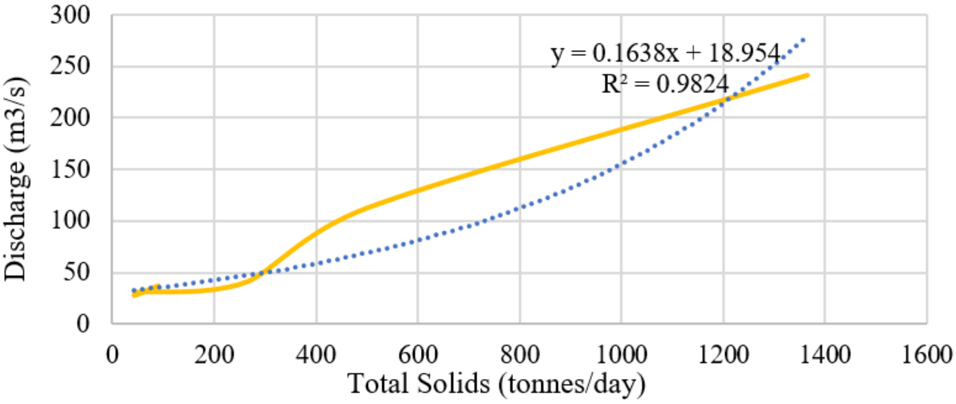

Figure 11. Sediment rating curve

3.3 Model Results

In addition to 2D flow and sediment transport, the HEC-RAS model produces better results when the mesh is well-positioned with the flow. After running a 2D unsteady flow simulation with the hydraulic model, another unsteady flow simulation was conducted, this time including the sediment model. The combined 2D model was run from 2003 to 2016 with a daily time step, producing results on bed level changes and other sediment-related outcomes. Calibration and validation of the combined 2D model were performed by adjusting the scaling factors and the morphological acceleration factor. The model provides key outputs such as bed change, bed elevation, sub-surface bed change, and sub-surface bed elevation, which are essential for determining the scour depth around the piers.

The primary focus during the simulation was the change in the bed level at the Kelanisiri bridge site, and it was observed that bed elevation changes were noticeably elevated near the bridge piers. Model computations indicated bed level changes of 3.2 m and 4.3 m around piers 1 and 2 (from the left bank) of the Kelanisiri bridge, respectively, following the 2016 flood event (Figure 12). The initial bed elevation was based on data from 2003. After the 2D model unsteady flow simulation, the bed level change around the piers from 2003 to 2016 was identified and that could be considered the scour depth relative to 2003.

To evaluate the performance of the sediment model combined with the hydraulic model, field observations were used. Accordingly, the 2D model simulated bed level changes at a cross-section 20 m upstream of the Kelanisiri bridge (Figure 13) and along a longitudinal section 20 m upstream of the bridge were compared with the observed field data on the Kelani riverbed level following the 2016 flood event (Figure 14). With the initial comparisons, the model was calibrated by adjusting the scaling factors related to sediment transportation.

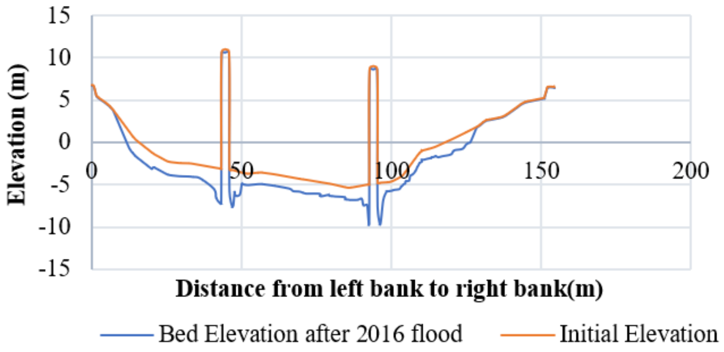

Figure 12. Riverbed elevation at the bridge site after the 2016 flood event

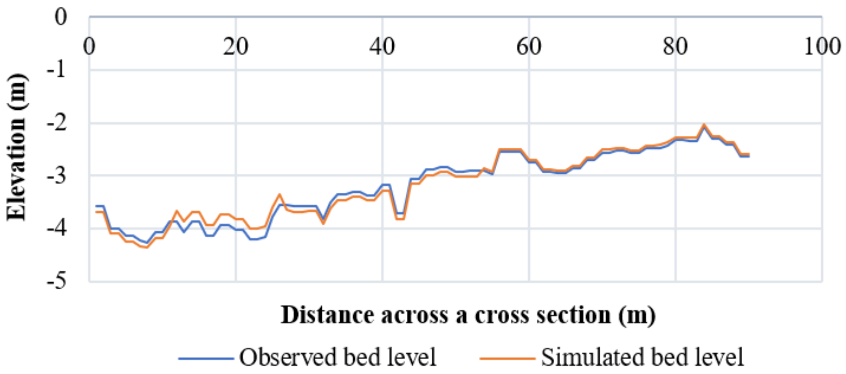

Figure 13. Comparison of model output with field data (Cross-sectional profile)

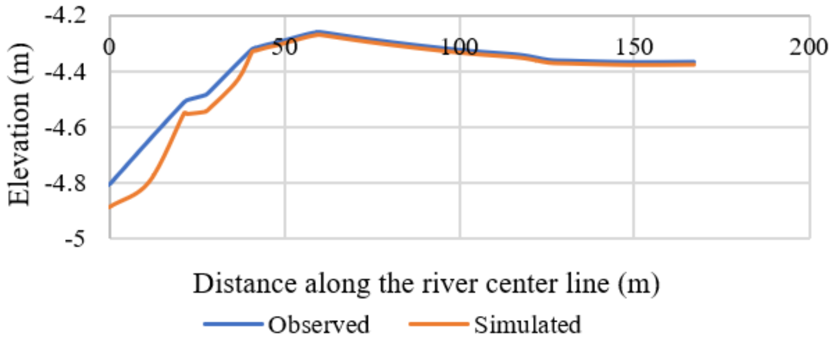

Figure 14. Comparison of model output with field data (Longitudinal profile)

4 Evaluation of 1D and 2D Model Performance

The scour depth computation is a subsequent step following the hydraulic analysis of the developed HEC-RAS model. The performance of the 1D and 2D hydraulic models was assessed using statistical parameters by comparing the model predictions with the observed data. The Pearson coefficient of determination (R^2), RMSE, and Nash-Sutcliffe efficiency coefficient (NSE) were used to assess the agreement between observed and simulated results. An R^2 value of 1 indicates that all variations in the dependent variable are explained by the independent variable. RMSE measures the magnitude of the prediction error, with lower values indicating better model performance as the predicted values are closer to the observed values. NSE ranges from $-\infty$ to 1, with a value of 1 indicating a perfect fit of the model to the observed values, while values below 0 suggest that the average observed value is a better predictor than the model predictions. Both the 1D and 2D modeling approaches were employed to estimate the scour depth around the bridge piers following the major flood event in 2016. A summary of the results is provided in Table 4. According to literature, an R^2 value greater than 0.7 has typically been considered applicable, indicating a strong correlation between numerical model simulated values and observed data or physical modeling data. RMSE values within 10-20% of the observed data and NSE values of less than 10% have been considered acceptable during the scour depth simulations.

As per the comparison between the statistical parameters on the model performance, it is evident that the 2D model demonstrates superior performance across all metrics, with an R2 value of 0.98 compared to 0.5 for the 1D model, indicating a much stronger correlation between model predicted values and observed scour depths. The RMSE value for the 2D model is significantly lower than the 0.4 for the 1D model, demonstrating greater accuracy in the 2D model. In addition, the NSE value for the 2D model is 0.92, comparatively higher than the 0.6 for the 1D model, indicating that the 2D model is more effective than the 1D modeling approach at reproducing the scouring effect around bridge piers. The discrepancies in performance can be attributed to the inherent advantages of the 2D model, which provides a more detailed representation of the flow field and better captures the complex interactions between hydraulic structures and flow. The 1D model, with its simplified approach, is unable to account for these complexities, leading to less accurate predictions. This comparison highlights the importance of using a 2D modeling approach, mainly in situations where accurate scour depth estimation is critical for the design and maintenance of hydraulic structures.

Table 4. 1D vs 2D model performance evaluation

Statistical Parameter	1D Model Results	2D Model Results
R^2	0.5	0.98
RMSE	0.4	0.13
NSE	0.6	0.92

5 Summary

Scouring tends to expose the foundation of a pier structure, jeopardizing its stability. The 1D model, unable to capture complex flow patterns and lateral flow velocities, particularly around the piers, often results in inaccurate scour predictions. In contrast, a 2D model can reliably predict and address the scouring effect, thereby enhancing the safety and integrity of bridge structures. The 1D model relies on empirical equations to estimate scour depth around bridge piers, whereas the 2D model integrates a hydraulic model with a sediment model to simulate bed-level changes around the piers. Preliminary assessments on scour depth can be approached via the 1D modeling due to its simpler and less computationally expensive nature but the simplicity arises from the reduced accuracy in capturing complex flow patterns around the bridge piers. Additionally, the HEC-RAS 1D model cannot account for variations in river topography.

When simulating scour. The 2D model was validated by using the field data available at very close proximity to the bridge structure. The HEC-RAS 1D model is only capable of providing the sum of local scour depth and the contraction scour depth around the pier, whereas the total scour depth is inclusive of the long-term bed degradation as well. Irrespective of the fact that the development of a 2D model is more complex compared to a 1D model, based on the nature of scouring action, it has become evident that the HEC-RAS 2D model suits well for the estimation of depth than the use of an empirical equation-based model simulation. Hence, it's clearly identified that the HEC-RAS 2D model surpasses the 1D model in estimating the scour depth around bridge piers. The 2D model is beneficial in situations where precise modeling is crucial. Thus, it can be concluded that the decision on the selection of the modeling approach is governed by the need for the accuracy of the measurement. Future research directions could focus on integrating machine learning techniques into scour modeling, potentially improving the accuracy of the estimations. In addition, advancement of the developed model to predict the depth of scour that could arise under the varying climate conditions in the future would pave the way for the implementation of suitable protective measures for the safety of bridge structures.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Acknowledgements

We wish to express our gratitude to the Civil Engineering Department of University of Moratuwa, Road Development Authority and Irrigation Department of Sri Lanka for the valuable support provided throughout.

Conflicts of Interest

The authors declare no conflict of interest.

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