# Application of HEC-RAS 2D model to Simulate Scour Depth Around Bridge Piers- A Case Study on Hanwella Bridge, Sri Lanka

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***Abstract***— *Lowering of the level of river bed due to water erosion is denoted by the term Scouring. Scouring can transpire around abutments and piers of a bridge. Pier scouring possesses a high threat to the stability of the bridge structures. The formation of vortices in the vicinity of bridges due to obstruction caused to the river flow is the core rationale behind this pursuit. Estimation of scour depth, which is the depth of the hole formed around a bridge pier due to scouring at a bridge site is indispensable in terms of the safety and economy of a bridge. Although various researchers around the world have developed numerical formulae and physical models for the simulation of scour around bridge piers, in the context of Sri Lanka, not many studies have focused on this area yet. In this study, HEC-RAS two-dimensional model is used for the determination of scour depth around the bridge piers of the Hanwella bridge built across the Kelani River of Sri Lanka. The change in bed elevation around the bridge pier provides the depth of the scour hole formed due to a considered flood event. As per the results, the hydraulic model coupled with the sediment transport model has produced a reliable estimation of the river bed level change and scour depth around the bridge piers. Further validation of the model results can be accomplished based on a series of laboratory-scale experiments.*

***Keywords***—scouring, piers, HEC-RAS, Kelani River

## I. INTRODUCTION

Scour is a common natural phenomenon occurring due to the interference of piers and abutments with the bridge structures and is referred to as the lowering of the level of river bed due to water erosion resulting in a susceptibility to expose the foundations of a bridge. The amount by which river bed lowers below the initial level of bed is denoted as depth of scour (Garde and Kothyari, 1998).

Scour eventuates around bridge piers, abutments, spurs, jetties, and breakwaters on the grounds of amendment of flow pattern and consequently increasing the local shear stress. Aftermath this uproots the material on the stream bed leading to the formation of scour holes. Coarser particles tend to diminish scour rate since those particles tend to accumulate in the scour hole. On account of the fact progression of scour holes around bridge piers is a threat to the stability of bridge structures, countermeasures to reduce the impact of scour are vital (Garde and Kothyari, 1998). More adverse impacts can be witnessed if the formation of scour holes around bridge piers is neglected since it's directly related to stability of the bridges. Bridge piers tend to fail when the scour together with the structural and hydraulic loads sabotage the foundation. The damage due to scour can range from minor erosion at an adjacent river bank or a bridge approach to a complete collapse of the bridge structure. When the upstream flow does not carry sediments into the area of scour, clear water scour occurs at the bridge site. On the contrary, live bed scour occurs at a bridge when the approaching flow tower is above the critical velocity for eroding sediments of a given size. When the piers and the abutments obstruct the river flow, the flow characteristics of the flow at the vicinity of such structures tend to change resulting in the formation of scour holes(Grimaldi *et al.*, 2009). A scour hole forms when river flow gets interrupted by the piers. Once the approaching flow hits the bridge structure, horseshoe vortices are formed in front of them. The total scour depth around a bridge pier is a combination of local scour, contraction scour and long-term bed degradations.

Recent studies have revealed the use of different kinds of models for the simulation of the scouring effect around the bridge piers. Dey et al.(2007) presented a kinematic model considering horseshoe vortex (HSV) motion in the scour hole.

Khosronejad et.al.(2012)conducted a numerical simulation to determine the local scour around bridge piers. In comparison with the laboratory flume setups used for the estimation of scour depth, numerical simulation can reduce costs and capture a better cognizance of the relevant flow and transport phenomena(Burkow and Griebel, 2016). There is a plethora of software available which could capture the scouring action around bridge piers like flo2dh, FLUENT, HEC-RAS, and SSIM. Among them the HEC-RAS (Hydrologic Engineering Centers River Analysis System) software incorporates sediment transport equations, provides detailed analysis of flow patterns, capable to model complex river geometries, and also offers a range of analysis tools. Furthermore, literature provides corroboration of the fact that two-dimensional(2D) models have outperformed in scour depth estimation in comparison with the one-dimensional models(Johnson, 1995; Yu and Yu, 2008; Sreedhara B M, Manu, 2016).

The HEC-RAS software is developed by the US Army Corps of Engineers for hydraulic modeling and analysis of river systems, channels, and bridge structures. HEC-RAS can simulate both one-dimensional and two-dimensional hydraulic modeling. Further, the software is freely available for use. The literature provides evidence about distinct attempts made by various researchers for the estimation of scour depth using a sediment modeling approach. The sediment transport routing technique has been used by Vaill (1997) to estimate the channel changes and pier scour depths at U.S. Highway 34 bridge on Surveyor Creek near Plainer, the U.S. Highway 40 bridge on the Yampa River near Maybell, and the State Highway 149 bridge on the Rio Grande at Wagon Wheel Gap. BRISTARS- Bridge Stream Tube model was applied for the bridge scour estimation using sediment transport routing. BRISTARS is capable of computing sediment transport as a function of shear stress, velocity, and some other variables. Shabani et al.(2021) used a coupled HEC-RAS 2D and WASP (Water Quality Analysis Simulation Program) to simulate the sediments. Even though quantifying the fate and transport of sediment and contaminants under flood conditions is an arduous task, the development of the HEC-RAS 2D model WASP external coupler had provided acceptable results. Further, they have suggested that the above-coupled model is a reliable tool for the prediction of the fate and transport rate of sediments. The advanced version of HEC-RAS which is inclusive of the two-dimensional sediment modeling capability can be directly used to assess the bed change, bed elevation, bed change rate etc. HEC-RAS has the potential to calculate the sediment transport at each grid cell of the 2D mesh. Brunner and Gibson (2005) conducted a study based on the sediment transport modeling in HEC-RAS and in their study, HEC-RAS sediment transport calculations have complied well with the results obtained from a laboratory study.

As per the records at the Road Development Authority many bridges in Sri Lanka have already been subjected to scouring around the bridge piers and much vigilance has not been paved upon this issue. Magalle bridge had collapsed in the year 2006 due to abutment erosion and scour damage (Rossetto *et al.*, 2007) Further, it has been reported that Manampitiya, Kotugoda, and Ruwanwella bridges to scouring around bridge piers. New piers were located parallel to existing bridges to minimize scouring at existing piers. This study is focused on the development of a two-dimensional HEC-RAS model to simulate the depth of scour around the bridge piers.

## II. HYDRAULIC MODELING OF RIVER FLOW

The HEC-RAS 2D modeling competence uses a finite volume solution scheme. The Navier-Stokes equations describe the motion of fluids in three dimensions. In the realm of channel and flood modeling, further simplifications are constrained. The shallow water equations are one such set of equations. The HEC-RAS 2D unsteady flow hydrodynamics assumes incompressible flow, uniform density, and hydrostatic pressure and the equations are Reynolds averaged with the intent turbulent motion is approximated using eddy viscosity.

A HEC-RAS 2D model refers to a hydraulic modeling approach that simulates flow and water surface profiles in two dimensions. The model incorporates equations that describe the conservation of mass and momentum to calculate the water surface elevations and velocities across the domain. By considering two-dimensional effects such as channel bends, floodplains, and other topographic features, the 2D model in HEC-RAS provides more accurate predictions of flow behavior, water depths, velocities, and inundation areas.

The governing laws for the two-dimensional model are the conservation of mass and the conservation of momentum.

Mass conservation:

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=q \tag{1}$$

Where $t$= time, $h$= water depth, $u$ and $v$ =velocity components in the x and y direction respectively, $q$=source/sink flux term.

Momentum conservation in x and y directions respectively:

$$\frac{\partial v}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial H}{\partial x}+\frac{gn^2|u|}{R^{4/3}}u=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial H}{\partial y}+\frac{gn^2|v|}{R^{4/3}}v=0 \tag{3}$$

$g$ is the gravitational acceleration(m/s$^2$), $n$ is Manning's coefficient and $R$ is the wetted perimeter(m). Even though the Saint-Venant equations (shallow water equation) are often simplified using diffusion wave approximations to reduce the computational time and the numerical instabilities the Shallow water equations were applied to the Kelani River due to the tidal influences(Samarasinghe *et al.*, 2022).

## III. SEDIMENT MODELING OF RIVER FLOW

A sediment transport model specifically focuses on the simulation of sediment transport and deposition processes in rivers and channels. Sediment modeling of the river flow using HEC-RAS can be accomplished by embodying sediment transport calculations into the hydraulic modeling process. With the incorporation of sediment transport processes, HEC-RAS two-dimensional sediment modeling facilitates to access the impacts of channel changes such as bank erosion or sedimentation, sediment deposition and scour. HEC-RAS sediment modeling approach involves simulating the movement and deposition of sediments in rivers and channels. The two-dimensional sediment transport solves a bed-material load transport equation but separates the bed-material load into bedload and suspended loads with empirical formulas. The transport equation is solved with an implicit Finite-Volume scheme on the same mesh as the hydrodynamics. Total load sediment transport refers to the sum of all particles transported. The total load transport equation is expressed as follows.

$$\frac{\partial}{\partial t}\left(\frac{hC_{tk}}{\beta_{tk}}\right) + \nabla.\,(hUC_{tk})= \nabla.\,(\epsilon_{tk}h\,\nabla C_{tk}) + E_{tk}^{HF} - D_{tk}^{HF} + S_{tk} \tag{4}$$

$\beta_{tk}$ =total load correction factor for the k$^{\text{th}}$ grain class

$C_{tk}$=total-load sediment concentration of the k$^{th}$grain class [ML$^3$]

$U$=depth averaged current velocity in j$^{th}$ direction [L/T]

$h$=water depth [L]

$\epsilon_{tk}$=total-load diffusion(mixing)coefficient corresponding to the $k^{th}$ grain class

$E_{tk}^{HF}$=total-load erosion rate in hydraulic flow [M/L$^2$/T]

$D_{tk}^{HF}$=total-load deposition rate in hydraulic flow [M/L$^2$/T]

$S_{tk}$=total-load source/sink term[M/L$^2$/T]

The main advantage of solving the total-load transport formula instead of separate bed- and suspended-load transport equations as in the one-dimensional modeling is the reduced computational costs since it requires one less transport equation solution and also simplifies the bed change and sorting computations. In HEC-RAS two-dimensional sediment modeling approach the bed change, sorting, and layering are simulated using a sub-grid approach. In this approach, each computational cell has two sets of curves for the horizontal wetted area and water volume as a function of elevation. In addition, each face also has two sets of curves for the wetted horizontal length and vertical wetted area as a function of elevation. The total bed change is computed as:

$$\Delta z_{bi} = \frac{1}{1-\phi_{bi}} \sum_k \frac{\Delta M_{bki}}{\rho_{sk}} \tag{5}$$

$\Delta z_{bi}$ = bed change for sediment subarea i [L]

$\Delta M_{bki}$= fractional mass exchange with the bed in subarea i [M/L$^2$ ]

$\phi_{bi}$=porosity of the eroded and deposited material [M/L$^3$]

$\rho_{sk}$= grain class particle density [M/L$^3$ ]

## IV. CASE STUDY ON HANWELLA BRIDGE

Hanwella bridge which is built across the Kelani River was selected for the case study. Kelani River basin in Sri Lanka is considered to be the second largest river basin. There are about 14 bridges constructed across the Kelani River and based on the availability of bridge geometry data the Hanwella bridge was selected for the study. The Hanwella bridge has a 110 m span and is 11.3m wide and consists of three elongated round nosed piers. This bridge has been exposed to scouring around the bridge piers and possess a threat to the stability of the bridge as well. Concerning the Kelani River basin, recurring flood events have been recorded for the years 2016, 2017, and 2018 consecutively(Samarasinghe *et al.*, 2022). Amidst them, the 2016 event has been catalogued as the most severe flood event in the recent past.

## V. METHODOLOGY

### *A. Overall Methodology*

Scour is not a one-dimensional activity. The Colorado State University (CSU) equation and the Froehlich equation are introduced within HEC-RAS software for the estimation of local scour around the bridge piers. The numerical equations have been developed for a one-dimensional model and accordingly, certain over and under estimation of scour depths have been reported in literature(Mohamed *et al.*, 2006).

In this study the two-dimensional modeling capability of the HEC-RAS software was exploited. Since the scour depth around a bridge pier in not the local scour alone this approach is more realistic than the use of numerical equations to predict the scour depth around bridge piers. The hydrodynamic model coupled with the two-dimensional sediment transport model is utilized for the determination of the scour depth around the bridge piers.

### *B. HEC-RAS hydraulic model and inputs*

*1) Modification of river bathymetry:* A digital elevation model developed using Light Detection and Ranging (LIDAR) was used as the terrain. Since the LIDAR data is not capable of representing the features beneath the water surface the measured river cross-section data were fed into the model (Podhoranyi and Fedorcak, 2015).

The river cross-section data obtained from a survey done in the year 2003 were incorporated into the model and were interpolated at 20m intervals. The river cross-section data generated geo tiff was combined with the LIDAR data to get a more accurate elevation model for the selected river stretch. Based upon the availability of data to be used as the boundary conditions for the model, the Kelani River stretch from Hanwella to sea outfall was chosen for modeling.

*2) Land use data:* The Kelani River basin is encountering rapid urbanization as well as commercialization, thus, confronts the most pressing water quality and other environmental issues in Sri Lanka, including loss of biodiversity(Surasinghe *et al.*, 2020). The lower Kelani basin is heavily urbanized and the upper Kelani basin is covered with greenery. The suggestions of Chow were taken into account when assigning Manning's coefficient. A separate polygon was created for the river channel to assign a manning's n value.

*3) Boundary Conditions:* The upper boundary condition was established as the hourly flow hydrograph at the Hanwella (Figure 1) whereas the hourly tidal fluctuation at the sea outfall was used as the lower boundary condition. Accordingly, the stage hydrograph at Nagalagam Street was able to reiterate the tidal variations entailing the backwater effects(Samarasinghe *et al.*, 2022).

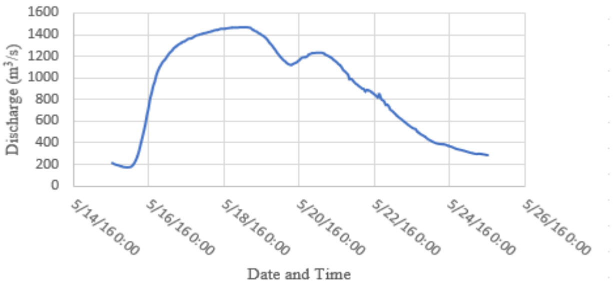

Figure 1. Flow hydrograph (2016 flood) as the upstream boundary condition for the model

*4) Calculation time step and mesh size:* The 2D mesh was created with a cell size of 50mx50m coarse sell resolution and the channel with 5mx5m fine cell resolution. The mesh was refined along the channel. The bridge piers were embedded into the terrain by modifying a clone of the original terrain. The time step was adjusted based on the Courant number. The Courant number plays a crucial role in determining the stability and accuracy of the simulation. In the context of HEC-RAS the courant number is used to ascertain the time step size. This number relates the size of the computational grid cells to the time step size. Accordingly, a time step of 60 seconds was selected for the simulation.

### *C.HEC-RAS two-dimensional sediment model and inputs*

*1) Development of the sediment model:* The two-dimensional sediment transport usually does not perform well with the diffusion wave equation and shallow water equations were adopted for the modeling. In order to extend the HEC-RAS hydraulic model to a sediment model the sediment data file was incorporated with the developed model. A well-constructed hydraulic geometry is imperative for a reliable sediment model.

A similar study has been done by Basser (2015) to assess the depth of scour around abutment. The consideration of $4d_{50}$ as the roughness value has pioneered best agreement with the experimental results during the simulation. Further, in comparison with the computed and measured bed changes, the Van Rijn sediment transport formula has proved to be in well agreement. Even though the Shen/Hung formula too had demonstrated proper results, the Van Rijn formula had outperformed the simulation (Basser *et al.*, 2015).

*2)Kelani River bed gradation:* The river bed gradation is an imperative component in sediment models. The HEC-RAS two-dimensional model encompasses a platform that included a bed gradation template. Sieve analysis was done at several locations of the Kelani River in pursuit of analysing the particle size distribution of the river. The mineralogical studies of the river bed sediments reflect quartz, biotite, feldspars, garnet and sapphire-rich composition. It has been noted that apart from quartz, biotite, feldspar, and garnet are also present. Mineral biotite and garnet are rich in small particle sizes such as 0.106 mm, 0.053 mm and 0.047 mm. Quartz is the mineral that is present in ample amounts in the Kelani River which is proof of the fact they are transported long distances from the origin.

*3) Initial conditions and transport parameters:* The selection of a transport model and Advection-Diffusion parameters is a vital component in the development of a two-dimensional sediment transport model. The model results are very sensitive to the selected function. After a careful review of the assumptions, hydraulic conditions and grain sizes for which each method was developed, the Wu method was selected for the simulation. The bed sorting method or the armoring method accounts for tracing the bed gradation to compute grain-class specific transport capacities. Since the developed model is two dimensional, the active layer sorting method was adopted. The fall velocity formula is used to calculate the free particle settling velocity of the sediments. Fall velocity method is not used as a calibration parameter due to its minor sensitivity for sediment routing.

*4) Sediment boundary conditions:* The rating curve boundary condition was adopted as the inflow sediment boundary condition for the model. The rating curve specifies the sediment load in tons/day or sediment concentration in mg/l as a function of flow discharge. The average amount of sediments in main Kelani River estimated by Mallawatantri (Silva, 2016), using measured turbidity and flow data, is about 2,350 t/ha/yr, at Hanwella bridge corresponding to a drainage area of 175,000 ha, after draining about 75% of the total basin area, indicating a sediment yield in the river about 0.134 t per ha per annum. The Central Environment Authority, Sri Lanka monitors the water quality at various locations of the Kelani River. Accordingly, the sediment concentrations along with the respective flow data were fed into the model as the input boundary condition at Hanwella.

### *D. Model Analysis*

*1) Hydraulic Model:* An excellent, calibrated hydraulic model is essential before the initiation for the sediment simulation. Accordingly, the developed hydraulic model was first calibrated and verified before the development of the two-dimensional sediment model. The 2016 flood was used for the calibration of the model. The model was calibrated by a trial-and-error procedure, adjusting the manning's roughness values. The calibration was followed by the validation of the model, executed via the 2018 flood event.

The statistical parameters, Pearson coefficient of determination ($R^2$), Root Mean Square Error (RMSE), and Nash-Sutcliffe efficiency coefficient (NSE) were used to check the better concurrence between the observed and the simulated results. An $R^2$ value of 1 suggests that all of the variations in the dependent variable can be interpreted by the independent variable. Further, the RMSE and the NSE values were also calculated to identify the compatibility between the observed and simulated values.

$$R^2 = \frac{\left(\sum_{i=1}^{n} (O_i-\underline{O})\ x\ \ (S_i-\underline{S})\right)^2}{\sum_{i=1}^{n} (O_i-\underline{O})^2 x (S_i-\underline{S})^2} \tag{6}$$

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n} (O_i-S_i)^2} \tag{7}$$

$$NSE=1-\frac{\sum_{i=1}^{n} (S_i-O_i)^2}{\sum_{i=1}^{n} (O_i-\underline{O})^2} \tag{8}$$

*2) Sediment Model:* The sediment model was utilized to identify the bed level changes near the piers of the Hanwella bridge. The bridge piers were embedded into the terrain model and separated as non-erodible surfaces during the simulation. The bed level of the Kelani River recorded after the 2016 flood event was used for the calibration of the model. The adopted transport function was calibrated using scaling factors. In practical applications, there is a lack of data availability to calibrate the bed and suspended load correction factors. There is a compromise between computational time and accuracy which in turn are proportionately minor. Generally, the morphology changes have proven to be more sensitive to other parameters and options such as transport function and adaptation parameters than the load correction factors.

## VI. RESULTS AND DISCUSSION

### *A. Comparison of 2016 and 2018 flood stages*

The highest recorded flood in the Kelani River after 1989 has been recorded in the year 2016(Arampola, Munasinghe and Kumari, 2021).The stages recorded at the Nagalagam Street gauge station were used for comparison. Following, Figure 2 and Figure 3 flaunt the comparison of observed and simulated stages at Nagalagam street gauge station for the 2016 and 2018 flood events respectively.

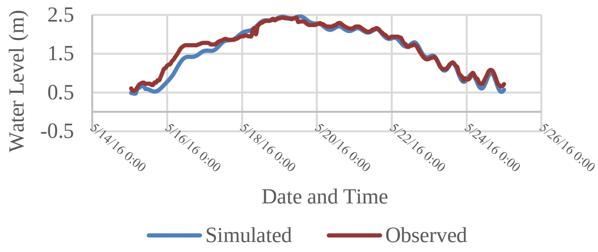

Figure 2. Comparison of stages at Nagalagam Street gauge station for the 2016 flood event

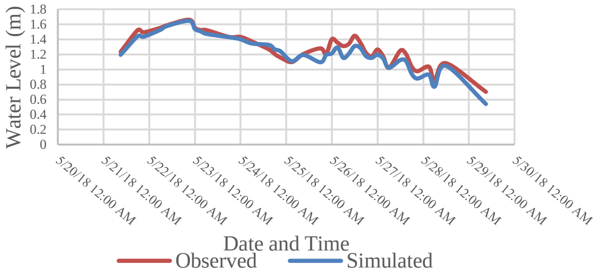

Figure 3. Comparison of stages at Nagalagam Street gauge station for the 2018 flood event

It is evident from the figures that the two-dimensional model well captures the time to peak as well. The hydraulic model performance was evaluated using statistical parameters.

Table 1. Evaluation of hydraulic model performance

| Statistical Parameter | 2016 flood event | 2018 flood event |
|---|---|---|
| $R^2$ | 0.98 | 0.97 |
| NSE | 0.98 | 0.72 |
| RMSE | 0.08 | 0.13 |

The obtained range of statistical parameters are at an acceptable level.

### *B. Sediment modeling output*

A two-dimensional model is capable of accurately predicting and mitigating scour related issues that could impact the safety of the integrity of bridge structures. In this study sediment transport model was executed for the 2016 flood event and the corresponding bed level changes as well as the other associated sediment results were obtained. The model provides bed change, bed elevation, sub face bed change, sub face bed elevation as the main outputs vital for the determination of the scour depth around the piers. The bed level change at the Hanwella bridge site was the main point of concern. A change in bed elevation was considerably high around the bridge piers. The model computations indicate a bed level change of 3.2m,3.5m and 3.8m respectively around pier 1, 2 and 3 (from the left bank) of the Hanwella bridge after the 2016 flood event (Figure 4). The initial bed elevation corresponds to the year 2003 and after the execution of the model the bed level change around the piers from the year 2003 to 2016 can be identified which could be considered as the scour depth with respect to the year 2003.

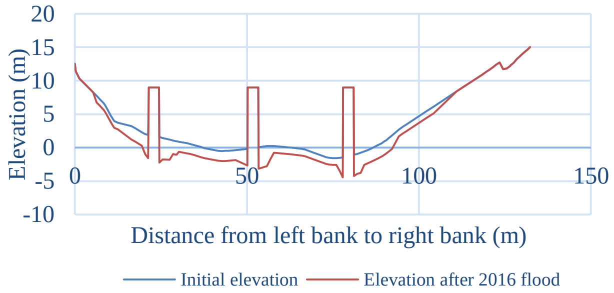

Figure 4. River bed elevation at the bridge site in the year 2003 and after the 2016 flood event- Model Output

The denoted total bed change around the bridge piers is the total scour depth around the pier. The sediment model performance was analysed by comparing the obtained bed level change at close proximity to the Hanwella bridge with the literature records on Kelani River bed level after the 2016 flood event (Figure 5).

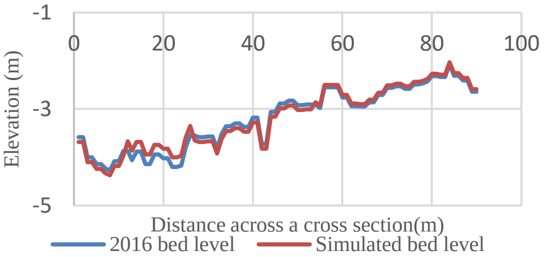

Figure 5. Comparison of model results with field data

The results comply well with the field observations obtained by the Irrigation Department Sri Lanka, after the 2016 flood event with statistical parameters $R^2$ value of 0.91 and RMSE of 0.1.

## VII. SUMMARY AND CONCLUSIONS

Scour at bridge piers is the core factor for bridge failure and perhaps reflects a potential threat to the civil population. As per the records of Road Development Authority Sri Lanka, considerable number of bridges have already been exposed to the threat of scouring around the bridge piers, and yet this has not been an eye-opening consideration. In this study, a numerical model is developed using the HEC-RAS software for the simulation of scour depth around the bridge piers. The hydraulic model is coupled with the sediment transport model for the determination of scour depth around the bridge piers of Hanwella bridge.

The pivotal objective of this study was to identify a reliable method for the estimation of scour depth around bridge piers. The results indicate that the HEC-RAS model is capable of depicting the bed level change associated with the formation of scour holes. The calibration of the model was conducted by changing manning's roughness coefficient and the scaling factors related to the sediment transport function respectively for the hydraulic model and the sediment model. A roughness coefficient of 0.35 was adopted for the river channel.

Both models were validated for similar flood scenarios that happened closer to the calibrated event. Since scour depth around bridge piers is a real-time measurement the next stage of the study aims at simulating the scour depth around bridge piers using a laboratory scale physical model for the validation of the numerical model results.

## REFERENCES

Arampola, A.M.U.B., Munasinghe, W.G.H.P.K. and Kumari, S. (2021) 'Analysis of flood frequency at lower reach of kelani river in Sri Lanka'.

Basser, H. *et al.* (2015) 'Modeling sediment transport around a rectangular bridge abutment', *Environmental Fluid Mechanics*, 15(6), pp. 1105–1114. Available at: https://doi.org/10.1007/s10652-015-9398-z.

Brunner, G.W. and Gibson, S. (2005) *Sediment Transport Modeling in HEC RAS by*.

Burkow, M. and Griebel, M. (2016) 'A full three dimensional numerical simulation of the sediment transport and the scouring at a rectangular obstacle', *Computers and Fluids*, 125, pp. 1–10. Available at: https://doi.org/10.1016/j.compfluid.2015.10.014.

Dey, S. and Raikar, R. V (2007) 'Characteristics of Horseshoe Vortex in Developing Scour Holes at Piers', (April), pp. 399–413.

Garde, R.J. and Kothyari, U.C. (1998) 'Scour around bridge piers', (4), pp. 569–580.

Grimaldi, C. *et al.* (2009) 'Countermeasures against Local Scouring at Bridge Piers : Slot and Combined System of Slot and Bed Sill', (May), pp. 425–431.

Johnson, P.A. (1995) 'Comparison of Pier-Scour Equations Using Field Data', *Journal of Hydraulic Engineering*, 121(8), pp. 626–629. Available at: https://doi.org/10.1061/(asce)0733-9429(1995)121:8(626).

Karami, H. *et al.* (2014) 'Verification of numerical study of scour around spur dikes using experimental data', *Water and Environment Journal*, 28(1), pp. 124–134. Available at: https://doi.org/10.1111/WEJ.12019.

Khosronejad, A., Kang, S. and Sotiropoulos, F. (2012) 'Experimental and computational investigation of local scour around bridge piers', *Advances in Water Resources*, 37, pp. 73–85. Available at: https://doi.org/10.1016/J.ADVWATRES.2011.09.013.

Mohamed, T.A. *et al.* (2006) 'Validation of Some Bridge Pier Scour Formulae and Models Using Field Data', *Journal of King Saud University Engineering Sciences*, 19(1), pp. 31–40. Available at: https://doi.org/10.1016/S1018-3639(18)30846-8.

Podhoranyi, M. and Fedorcak, D. (2015) 'Inaccuracy introduced by LiDAR-generated cross sections and its impact on 1D hydrodynamic simulations', *Environmental Earth Sciences*, 73(1), pp. 1–11. Available at: https://doi.org/10.1007/S12665-014-3390-7.

Rossetto, T. *et al.* (2007) 'The Indian Ocean tsunami of December 26, 2004: Observations in Sri Lanka and Thailand', *Natural Hazards*, 42(1), pp. 105–124. Available at: https://doi.org/10.1007/s11069-006-9064-3.

Samarasinghe, J.T. *et al.* (2022) 'Comparing Combined 1D/2D and 2D Hydraulic Simulations Using High-Resolution Topographic Data: Examples from Sri Lanka—Lower Kelani River Basin', *Hydrology*, 9(2). Available at: https://doi.org/10.3390/hydrology9020039.

Shabani, A. *et al.* (2021) 'A coupled hydrodynamic (HEC-RAS 2D) and water quality model (WASP) for simulating flood-induced soil, sediment, and contaminant transport', *Journal of Flood Risk Management*, 14(4). Available at: https://doi.org/10.1111/jfr3.12747.

Silva, K. (2016) *Medium to long term Multi Stakeholder Strategy & Action Plan for Management & Conservation of the Kelani River Basin*. Available at: https://www.researchgate.net/publication/323336610.

Sreedhara B M, Manu, P.U. (2016) 'Comparative Study on different Bridge Scour Monitoring Techniques : A Review', (March), pp. 17–19. Available at: https://doi.org/10.13140/RG.2.1.3197.1925.

Stephen Holnbeck, B.R. and Parrett, C. (1997) *Method for rapid estimation of scour at highway bridges based on limited site data Water-Resources Investigations Report 96-4310 Prepared in cooperation with the Montana department of transportation*.

Surasinghe, T. *et al.* (2020) 'Challenges in biodiversity conservation in a highly modified tropical river basin in Sri Lanka', *Water (Switzerland)*, 12(1). Available at: https://doi.org/10.3390/w12010026.

Yu, X. and Yu, X.B. (2008) '1D and 2D Hydraulic Simulations for Bridge Scour Prediction : A Comparative Study', pp. 226–232.