Validation of Bridge Scour HEC RAS Model Using Propagation Error Analysis

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Abstract. The scouring phenomenon is one of the causes of bridge damage in the world. This scouring phenomenon has various kinds such as local scour and contraction scour. There are various equations for calculating pier scouring, including Colorado State University equations, Frochelin and others. A computer program is needed to facilitate the calculation of pier scouring, HEC-RAS based on Finite Difference Method was chosen to simulate pier scouring problem. Up until now, there has not been any research to quantify the uncertainty of bridge scour HEC RAS based of experiment. The objective of this study to validate the pier scouring calculation by comparing the expected value of pier scouring results of HEC-RAS with an experiment and CSU equation. The HEC-RAS was evaluated using experimental data that had been carried out by Shukri in 2017. Furthermore purpose of this study is determining which the variable that is sensitive to the depth of scouring. The sensitive variables are determined by performing sensitivity analysis of the variables on HEC-RAS using the Pearson correlation coefficient method and regression analysis. Error propagation is done to get the uncertainty value from pier scouring due to the influence of sensitive variables.

1. Introduction
Scour is the result of grinding due to water flow, which lifts material from the riverbed and riverbanks around the piers and bridge abutments [1]. The scour phenomenon needs to be considered because it will reduce the carrying capacity of the soil due to eroded soil. If the bridge piers or foundation is not strong enough to withstand the force of the water flow and the bridge load, a bridge piers is collapsed or shifted.

There are two types of scour, namely local scour and contraction scour. This study focuses on the phenomenon of local scour which involves grinding the material around the piers, abutment, and river embankment. This results in a decrease in the surface of the riverbed which causes a decrease or shift in the piers or abutment. The scouring pattern that occurred on the pier was horseshoe, with the flow of water that was bigger make deeper into the scour [2,3]. Local scouring around the bridge piers occurs due to the flow of water held by the piers, horizontal flowing water will be held back by the bridge piers and form a rotation system [4,5].

This numerical study quantified the depth of pier scouring by using the HEC-RAS based on experiment conducted by Shukri in 2017 [6]. The equation of scouring is the result of momentum conservation law by applying the conservation law of mass, in 1992, Richardson found an equation for calculating depth pier scouring called CSU Equation [7]. The CSU equation was equation that used in the HEC-RAS.
The purpose of this research is to validate the HEC-RAS to calculate the pier scouring depth. The sensitivity analysis for pier scouring caused by some variables was evaluated. The studied variables were velocity of water flow, flow depth, and discharge. The expected value of pier scouring depth from the simulation results of HEC-RAS will be compared with one obtained by the experimental results [6] and CSU equation-

2. Pier scouring
Scouring was the result of erosive actions of flowing water, by dredging and carrying away material from the bottom and riverbanks and from around the bridge pier and bridge abutments [7]. Different types of material will produce different scour, such as cohesive soil (clay) will be more difficult to erode compared to non-cohesive (sand) soil.

Local scour in the pier is a function of the characteristics of riverbed material, basic configuration, flow characteristics, fluid properties, and pier geometry. The material characteristics are granular or non-granular, cohesive or non-cohesive, erodible or rock that cannot be defined. Granular bed material ranges from small to large stones and it is characterized by D50 and rough sizes such as D84 or D90.

CSU equation is the recommended equation by the US highway administration transportation department to calculate the depth of pier scouring:

\[
y_2 = 2.0K_1K_2K_3 \left( \frac{a}{y_1} \right)^{0.65} F_{r_1}^{0.43}
\]

where, \(y_2\) = scour depth, \(y_1\) = flow depth directly upstream of the pier; \(F_{r_1}\) = Froude number; \(K_1\) = correction factor for pier nose shape; \(K_2\) = correction factor for angle of attack of flow; \(K_3\) = correction factor for bed condition; \(a\) = pier width.

Richardson has determined the values of the correction factors needed in the CSU equation [7]. For the pier shape correction factor \((K_1)\), the value ranges is from 1.1 - 0.9, depending on the shape of the pillar. Flow direction correction factor \((K_2)\) is determined based on flow angle, pillar length and pillar diameter, with a range of 1 - 5. The bed material correction factor is determined by the size of the grain, with a value of 1.1 - 1.3.

3. Method
There are 4 stages to complete this study. First stage is the process of collecting data for the pier scouring input process in the HEC-RAS application, which is in the form of river geometry data, water flow data, and soil data. The data is taken from the results of the experiment [6]. There are also hypothetical data for cross sections of rivers and bridge structures.

The second stage is performing numerical simulation by using HEC-RAS and data obtained in stage 1. Numerical modelling is done with 3 scenarios. Scenarios are performed to see variables that have a significant effect on the depth of pier scouring, and it is estimated that there are three studied variables that have the effect on pier scouring depth from several input parameters needed in HEC-RAS modelling. The first scenario is the variation of flow depth with the variation of 0.01 – 0.1 m, the second scenario is water velocity with the variation of 0.045 – 0.54 m/s, and the third scenario is flowrate with the variation of 1.57 – 25.1 dm³/s. The scenarios are carried out on three different pile diameter variations which are 5.5 cm, 7.5 cm, and 11 cm.

The third stage is carried out by performing sensitivity analysis of the simulation results of three scenarios on HEC-RAS. Sensitivity analysis is performed to see the effect of each variable on pier scouring depth by using the Pearson method about correlation coefficient data processing. Correlation coefficient (R) is a value that indicates the strength or absence of a linear relationship between two variables. There is a correlation relationship created by Pearson, so that is called Pearson correlation. The value of R is -1 to +1, where when the value of R approaches 1 or -1, then the relationship between the two variables is strong, whereas if the value of the variable approaches 0, then the variable has a weak relationship. From the Pearson value, it can be determined that the depth of pier scouring can be called sensitive to the variable varied [8]. This is the equation of Pearson:
\[ R = \frac{n \sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{\sqrt{n \sum_{i=1}^{n} X_i^2 - \left( \sum_{i=1}^{n} X_i \right)^2} \sqrt{n \sum_{i=1}^{n} Y_i^2 - \left( \sum_{i=1}^{n} Y_i \right)^2}} \] (2)

The final stage is done by examining the error analysis to compute the uncertainty from the depth of pier scouring due to the influence of three studied variables. Error analysis is a study and evaluation of uncertainty in measurement. In a measurement, it is obtained the best estimation results of observations and there is also an uncertainty of observations whose results are a range or expected value of measurement. The above statement, can be express by the following equation:

\[ x = x_{\text{best}} \pm \delta x \] (3)

\[ \delta q = \sqrt{\left( \frac{\partial q}{\partial x} \delta x \right)^2 + \cdots + \left( \frac{\partial q}{\partial z} \delta z \right)^2} \] (4)

The expected value of pier scouring depth will be obtained from the simulation results using HEC-RAS. From the result, it can be compared the simulation results using HEC-RAS with the experimental results and literature entered between the upper limit and lower limit of the result or not. If it enters the interval, the result can be accepted.

4. Result and discussion

Modelling is done by entering the needed data in the HEC-RAS. Pier scouring depth is obtained after running the bridge scour window based on the number of variations in scenario parameters and 3 variations diameter of the bridge pillar. There are 111 pier scouring model in HEC-RAS, that divided to 30 running of scenario 1, 36 model of scenario 2, and 45 model of scenario 3. In scenario 1, with variations in the value of water depth \( y_1 \), and the input value of water velocity \( V \) 0.225 m/s. In scenario 2, with variations in the value of the water velocity \( V \), and the input flow depth value \( y_1 \) 0.03 m. In table x shows the results of 15 experiments in scenario 1, with variations in the value of water discharge \( Q \). The depth of pier scouring \( (D_s) \) simulation of HEC-RAS with variations of pile diameter: A = 5.5 cm, B = 11 cm, and C = 7.5 cm. In figure 1 there are graphics of scour depth \( (D_s) \) versus the variated parameters.

![Ds VS Y](image-url)
4.1. Sensitivity analysis

Based on the results of data processing from the 3 simulation scenarios performed, it can be concluded that the pier scouring parameter ($D_s$) tends to be the most sensitive to the water flow velocity variable ($V$), because and its coefficient correlation ($R$) approaches 1 from 3 scenario. The coefficient correlation is calculated using equation (2) for 3 variation scenarios. Sorted from the highest to the lowest value, the parameters that have a significant effect on pier scouring depth ($D_s$) are the velocity of the water flow ($V$) with $R = 0.97$, the discharge ($Q$) with $R = 0.94$, and into the flow depth ($y_1$) with $R = 0.91$.

**Figure 1.** Scour depth vs: (a) Flow Depth; (b) Velocity of water flow; (c) Discharge from running HEC-RAS
4.2. Error analysis
The velocity of water flow (V) is the parameter that has the most influence on the depth of pier scouring (Ds), followed by discharge (Q), and flow depth (y1). The three variables have a coefficient correlation (R) which is close to one and is included in the range 0.8-1, which is categorized as having a strong relationship. Therefore an error propagation is calculated to find the uncertainty value ($\delta Ds$) from the depth of pier scouring (Ds) due to 3 variables.

The uncertainty value ($\delta Ds$) can be searched using the slope and standard deviation values of the variables that affect the depth of pier scouring (Ds) from each scenarios. There are 3 uncertainty values ($\delta Ds$) for 3 variations in pier diameter. The expected value from the depth of pier scouring ($\delta Ds$) is obtained by adding or subtracting the value of the best estimate with the uncertainty value (Ds), equation (3). Then the uncertainty value ($\delta Ds$) is obtained and the expected value of pier scouring depth (Ds) for the 3 diameter variations is as follows, the uncertainty ($\delta Ds$) of type A, B, and C, are 0.024 m, 0.038 m, and 0.031 m.

4.3. Validation
Pier scouring is calculated in 3 different diameters of 5.5 cm, 11 cm, and 7.5 cm. The expected value of pier scouring were obtained in the form of adding the results of running HEC-RAS plus or less with the uncertainty ($\delta Ds$) that had been calculated use equation 3. The pier scouring depth (Ds) of the experimental results and the CSU equation will be compared with the expected value of pier scouring (Ds) as a result of the HEC-RAS simulator as a validation process. If the value of pier scouring (Ds) by the experimental result and the CSU equation is in the expected value, the results of HEC-RAS are acceptable, if is not then the simulation results of HEC-RAS are not accepted.

![Comparison chart of pier scouring depth: HEC-RAS, CSU equation, and experiment](image)

Based on figure 2, the depth of pier scouring (Ds) as a result of the CSU equation and the experiment entered into the expected value is the result of the HEC-RAS simulation propagation error. The simulation performed on the HEC-RAS results is acceptable when compared with the results of CSU equation calculations and experiments. The expected value for pier type A, B, and C are 0.08 ± 0.0247 m, 0.13 ± 0.0389 m, and 0.1 ± 0.0311 m. This shows that the simulation results of HEC-RAS are acceptable.

5. Conclusion
The biggest influence on pier scouring depth (Ds) is the velocity of water flow (V), with a value of $R = 0.97$. The second largest influence is the flow discharge (Q) with a value $R = 0.94$. The last is the flow depth ($y_1$) with $R = 0.91$. The depth value of pier scouring is sensitive to changes in variables, with the most sensitive sequence being the velocity of water flow (V) [m], water flow discharge (Q) [m³ / s], and water depth ($y_1$) [m] (inflow). These parameters affect the results of
scouring depth, so uncertainty is sought, as the tolerance value of the depth scouring results of HEC-RAS. Uncertainty is added to the scour depth value of the HEC-RAS results to produce the expected value.

The HEC-RAS generates scouring depth values as the best estimate value. This value is added to the uncertainty of the results of the error propagation so, it becomes expected value of the depth of scouring. The expected scour depth of HEC-RAS for pile type A, B, and C are $0.08 \pm 0.0247$ m, $0.13 \pm 0.0389$ m, and $0.1 \pm 0.0311$ m. The results of the scouring depth were compared with the results of experiments and CSU equations were compared to expected value. The depth value of pier scouring from the CSU equation and the experiment is entered into the expected value so that the HEC-RAS is can be used to find the pier scouring depth.

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