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Probabilistic Prediction of Scouring around Piers using Monte Carlo Simulation

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Lect. Dr Ali Hussein Jaber Al Rammahi [1] and Prof. Dr Saleh Issa Khassaf [2]
[1] College of Engineering, University of Kufa, Iraq E-mail alih.jabir@uokufa.edu.iq
[2] College of Engineering, University of Basrah, Iraq E-mail salehissakh@gmail.com

Abstract
Assessing local scour around a pier is important in terms of creating a good design for any bridge. Many equations are available to predict local scour around pier, though the reliability of these must be checked using statistical tools. A Monte Carlo simulation was thus used in this study to check the probabilistic accuracy of lab equations of local scour around a test pier so that the observation data and prediction equation were both tested probabilistically before use in simulation. The parameters of the prediction equation were specified based on the probabilistic and deterministic variables, with average velocity, critical velocity, water depth, median bed diameter, and Froude number being the unknown variables. The deterministic variables were the diameter of the pier and the spacing from the pier to the abutment. The optimum number of iterations utilised in the Monte Carlo simulation was also investigated based on standard deviation. The independent terms of the prediction equation for the simulation model were derived based on the original distribution of the equation of local scour and the relevant statistical values. The distribution of observation data of local scour was assumed to be normal, while the simulation model was lognormal. The input data was then used to check the probabilistic outcomes of the deterministic equation. The deterministic equation of local scour gave the results at the corresponding confidence level of about 20%, depending on the curve of a cumulative probability distribution. The probabilistic results were thus deemed preferable for the computation of local scour around the pier.
Keywords :pier, local scour, Monte Carlo simulation

1. Introduction

The main reason for bridge failure is scouring around piers and abutments, which can negatively affect both rail and road networks [1]. In the United States, this phenomenon has previously given rise to the failure of about 400,000 bridges over various watercourses [2] [3]: the Missouri river flooded in 1993, for example, causing the collapse of twenty-two bridges due to scour, with losses of about $8,000,000 [4]. There are three main types of scouring, general, contraction, and local scour [5], though this study focuses on local scour. This type of scour removes sediments around a pier or abutment [6], and the mechanism of local scour around piers is the downward flow at the upstream face, which causes vortices at the base of the river [7]. The approach velocity of flow at the pier face is decreased and the pressure increased at a point known as the stagnation point. The downflow then quickly reaches a maximum, especially at bed level, causing the scouring of sediment [5].

There are three main ways to simulate an uncertainty problem, the analytical, approximate, and Monte Carlo methods. Analytical methods require mathematical assumptions to be applied to explain the problem in a simple form, though these methods can be very effective. Approximate methods describe the statistical characteristics as approximations of output of random variables; these methods include options such as the First Order Second Moment Method (FOSMM). The third method is Monte Carlo, which generates values randomly for uncertain variables and uses these to solve deterministic equations [8]. Tubaldi et al [9] suggested a probabilistic framework to estimate scour using a Markovian approach for recording memory effects in scour development, and then applied the simplified numerical examples to explain the proposed framework. Johnson [10] examined bridge failure due to local scour by examining the relationship between the risk of failure and factors of safety by combining the uncertainties of design parameters with an example to explain the probabilistic approach. In this study, Monte Carlo simulation was used to estimate the reliability of estimations of scour depth around a pier using measurements, based on previous data about scour depth around the pier gathered in the lab, then utilising this example to examine the reliability of the scour depth predicted by the specified equation.

2. Methods

Lab data on local scour around a circular pier and the respective prediction equation were used in a probabilistic simulation using Monte Carlo techniques. Abbas [11] measured the scour around circular piers and abutments based on multiple lab tests, and the results from that research were used to apply dimensional analysis techniques and statistical methods to develop an empirical equation for scour prediction. Equation 1 can thus be used to forecast local scour around such a pier [11].

$$\frac{ds}{D} = 60.01\left(\frac{X}{D}\right)^{0.08}\left(\frac{V}{V_c}\right)^{6.74}\left(\frac{d_{50}}{D}\right)^{0.97}\left(\frac{y}{D}\right)^{-0.24} Fr^{-1.89} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

where ds is the scour depth (L); X is the face to face distance between pier and abutment; D is the pier diameter (L), ranging from 1.5 cm to 4 cm; V is the approach mean velocity (L/T); V_c is the critical velocity (L/T); d_{50} is the sediment median size (L); y is the flow depth (L); and Fr is the Froude number (dimensionless). Figure 1 illustrates the application of this equation, clarifying the symbols for the scour depth equation. This formula offers a coefficient of determination (R^2) of 0.86, suggesting a strong correlation between the observed and predicted values [11]. The equation was derived using the least-squares method.

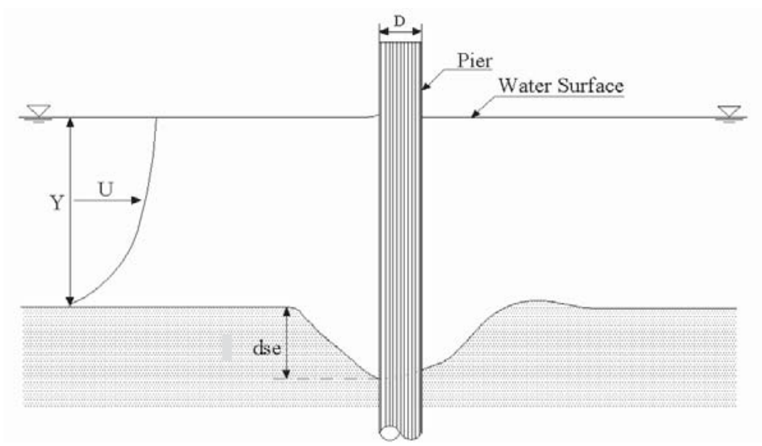

Figure 1: Section profile of scouring around the circular pier [12]

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The modelling of engineering problems is hampered by the uncertainty created by the randomness of natural phenomena, which often lead to inaccurate assumptions [13]. All parameters of equation 1 are thus technically uncertain, except for the dimensions of the pier (D) and the distance between the pier and the abutment (X). Physical randomness and statistical uncertainty mean that the characteristics of the other actual system parameters cannot be described in detail [14].

For complex problems, the Monte Carlo technique offers a powerful numerical method of simulation [15], producing numerical results without the need for physical testing [16]. The Monte Carlo technique is thus an important tool for assessing and evaluating the risk or reliability of a complex engineering system, based on an understanding of probability and statistical principles [17]. The Monte Carlo simulation procedure can be summarised by six steps, based on the assumption that the dependent variable, y, is a function of a set of independent variables x1, x2, ….,xn, and that one or more of these variables displays some uncertainty [18]:

1- Specify all uncertain variables.
2- Assign all uncertain variables in terms of their probability distribution functions (PDFs).
3- Produce data for the uncertain variables.
4- For each iteration, define the problem deterministically for the uncertain data.
5- Based on the number of iterations (N), extract the probabilistic information.
6- Compute the accuracy of the simulation.

Based on these output values, the statistical sample can be used to produce a histogram, frequency diagram, and Probability Distribution Functions (PDF) and corresponding Cumulative Distribution Function (CDF) figures.

3. Results and discussion

The deterministic and uncertain variables in equation 1 were assigned as the first step of this study, as illustrated in Table 1. All parameters in the equation are uncertain variables (probabilistic) with the exception of the distance between the pier and abutment and the diameter of the pier (X/D) due to a lack of measurement accuracy in the field. The values of local scour around the pier (ds) obtained from the ratio in the applied equation (ds/D) are thus probabilistic, and the results for local scour are heavily dependent on the four uncertain variables and their distribution types.

Table 1. Input variable types

Variable symbols	Type
X/D	Deterministic
V/Vc	Probabilistic
d_{50}/D	Probabilistic
y/D	Probabilistic
Fr	Probabilistic

Abbas [11] utilised only the value of the coefficient of determination, using the least-squares method to predict the form of equation 1. Use of the least-squares method must satisfy the following conditions:

1- Observation data is assumed to have a normal distribution. The assumption of normality test using the Kolmogorov-Smirnov method with confidence level of 95% (α = 5%) requires the following hypothesis:
  - The null hypothesis H_0: The distribution is normal;
  - The alternative hypothesis H_1: The distribution is not normal

Figure 2 shows that, in this case, the P-value is equal to 0.093, which is more than 0.05; the null hypothesis is thus not rejected, and the distribution of observation data can be assumed to be normal. This condition was thus achieved.

2- The residual values must be satisfied based on three conditions. The residual data is left after subtracting the values of the observation measurements of local scour from the predictions of equation 1.

A- These values must be distributed normally, tested according to the assumptions of the Kolmogorov-Smirnov method. Figure 3 illustrates that the P-value in this case is equal to 0.15, which is greater than 0.05. Thus, the null hypothesis is not rejected, and the distribution of the residuals can be assumed to be normal.

B- The relationship between the residual values and the predictions of local scour data from equation 1 should be non-uniformly distributed, Figure 4 indicates that this condition was met in this case.

C- A successful Durbin Watson test of the dependence of the residuals based on coefficient values is required [19]. The test statistic of residual values in this case was d=0.82, with the upper and lower criteria values being 1.7674 and 1.3944 respectively. The test value was thus between the lower value, 1.3944, and zero, identifying correlation of residuals, and satisfying this condition .

Based on the statistical tests, there should be no problem deriving the local scour equation using the least-squares method.

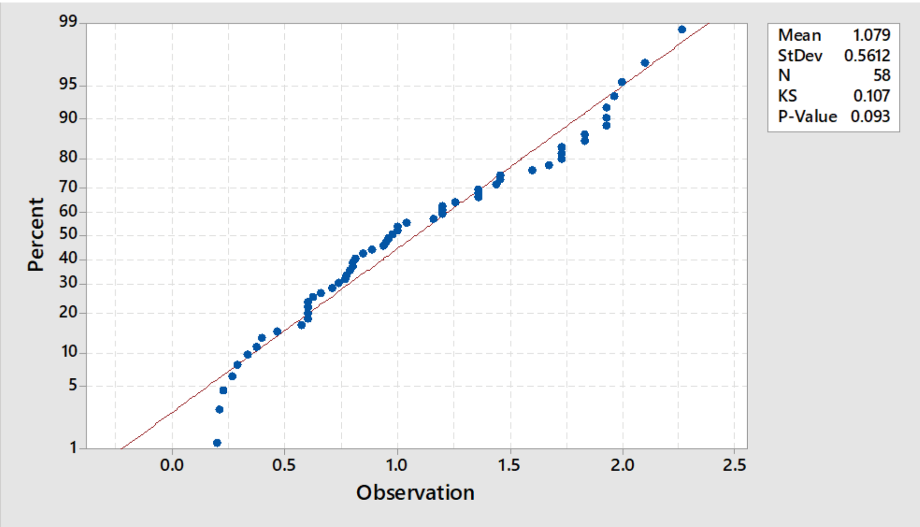


Figure 2: The distribution of observation data of local scour

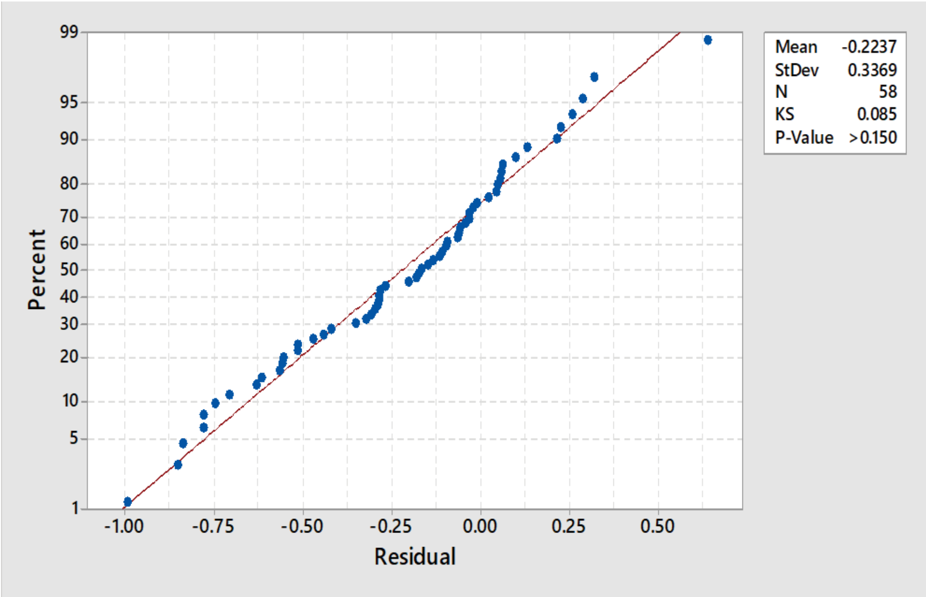


Figure 3: The distribution of residual data

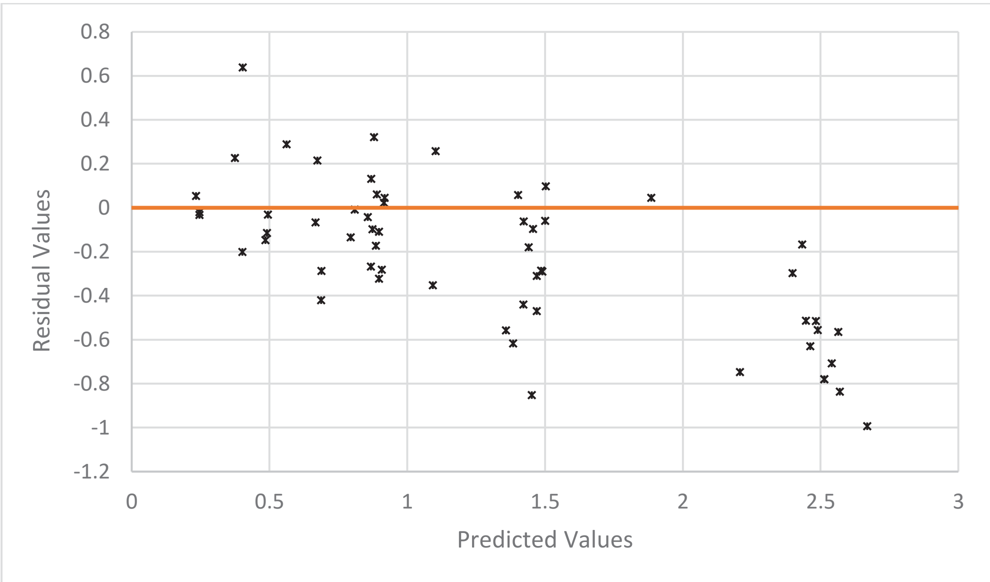
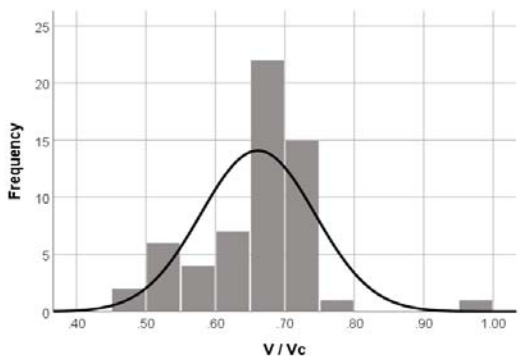


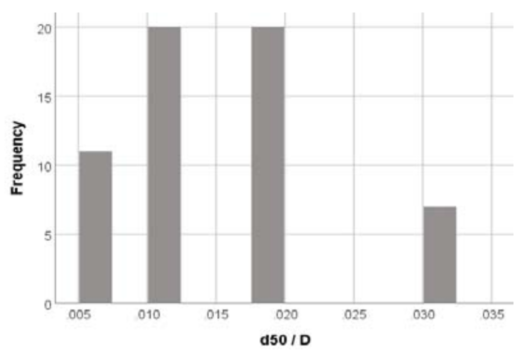
Figure 4: The relationships between residual and prediction values

The distribution of independent probabilistic variables in equation 1 was then investigated to generate the model used for Monte Carlo simulation. Figure 5 shows the distribution types of each variable, with the maximum, minimum, mean, and standard deviations of the observation data as illustrated in Table 2. The ratios between the average velocities over the critical and Froude number values are scattered normally, while the median diameter and water depth over the diameter of pier data are distributed lognormally. A number of iterations for the simulation model had to be selected to compute the reliability of equation 1; based on the data above, the observation data of local scour distribution was normally distributed, so the standard deviation value of the first trial of iteration number (N) was set equal to 1,000, as this approximates the value of standard deviation for N = 100,000 as illustrated in Table 3 and Figure 6. Iteration numbers corresponding to N = 1,000 were thus used to simulate each independent parameter of local scour as used in equation 1. Statistical software techniques were utilised to generate the probabilistic values for equation 1 based on statistical parameters values ranging between the maximum and minimum randomly generated using a Monte Carlo model. Each independent part of the prediction equation for local scour, based on distribution type, was thus determined using Monte Carlo simulation, and the mean and standard deviations of each simulation parameter are illustrated in Figure 7, with deterministic values X/D assumed in order to obtain prediction values for local scour around the pier.

By inputting all probabilistic parameters obtained from Monte Carlo simulations and the three values of X/D, a thousand values for prediction of scour for each case were generated as output data, as seen in Figure 8. The lognormal distribution of the prediction values was obviously a result of the thousands of iterations of data.

To check the reliability of the local scour equation, the first step was to select the deterministic value of X/D, which was set to 4.4. The second step was to draw the cumulative probability distribution for the prediction of local scour using Monte Carlo simulation, as shown in Figure 9. The final step was to select the values of each parameter of the equation, so that V/Vc, Fr, d50/D, X/D, and y/D were set equal to 0.546, 0.178, 0.0116, 4.4, and 2.18 respectively. IBM SPSS software was used to simulate the Monte Carlo model, and by inputting the values above into equation 1, the deterministic value of ds/D was found to be equal to 0.33. The probabilistic value of ds/D, taken from Figure 9 with a confidence level of 90%, was about 3. The value of deterministic local scour as produced by equation 1, taken from Figure 9 , thus corresponded to a confidence level of 20%. This suggests that the probabilistic value of scouring is more accurate than the value computed by equation 1.





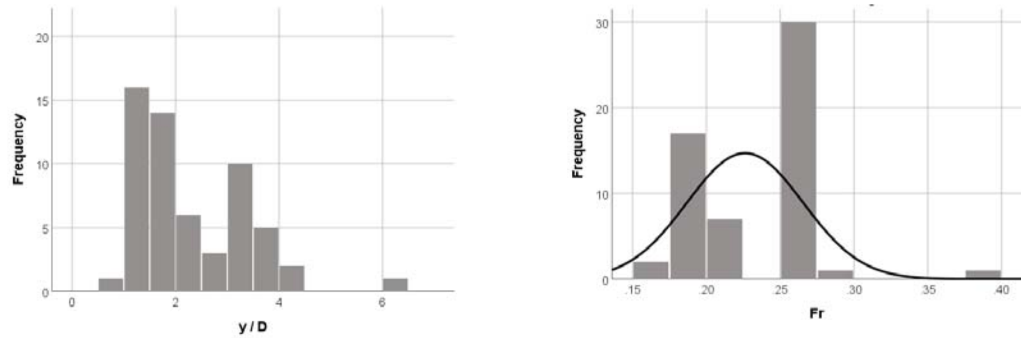


Figure 5: Distribution of independent variables types

Table 2: Input variable observation values for scour around the pier

Name	Statistical values		Distribution	Maximum and minimum values
	Mean	Standard deviation		
X/D	-	-	-	1.875 – 9.0
V/Vc	0.6612	0.0821	Normal	0.968 – 0.492
d_{50}/D	0.01565	0.00722	Lognormal	0.00725 – 0.031
y/D	2.2617	1.0432	Lognormal	0.75 – 6.0
Fr	0.2262	0.03934	Normal	0.159 – 0.387

Table 3: Statistical parameters for prediction data in each iteration

Statistical parameter	Number of iterations			
	N=1000	N=10000	N=20000	N=100000
Mean	1.161	1.154	1.151	1.150
Standard deviation	0.517	0.503	0.5001	0.499

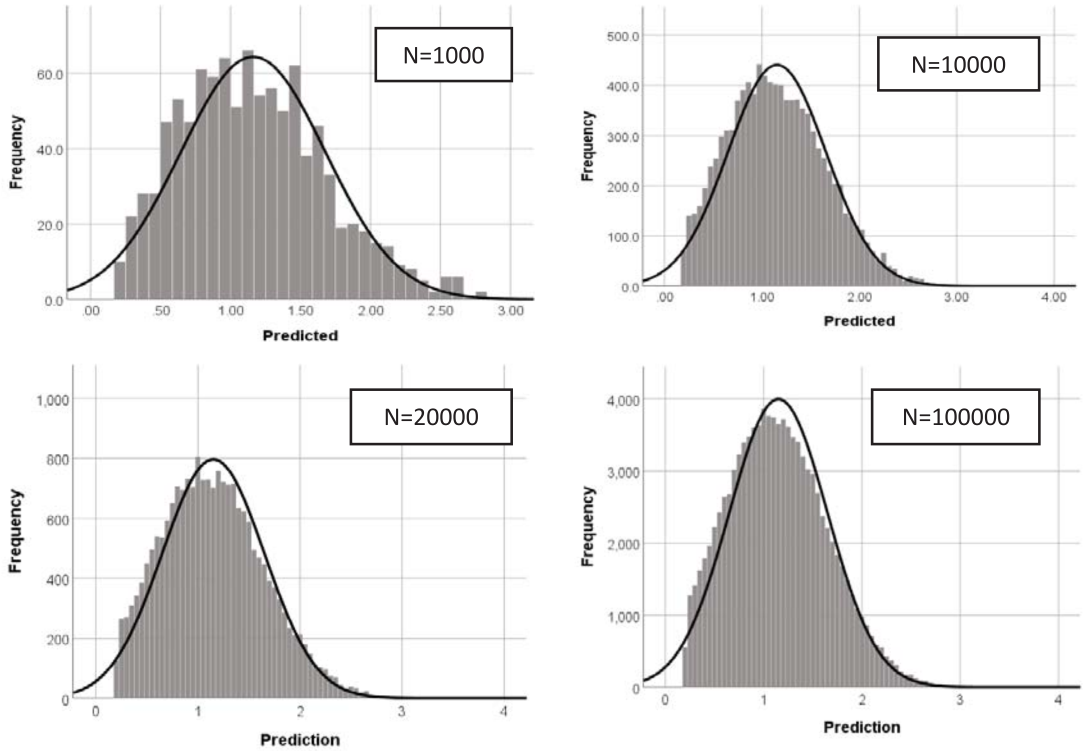
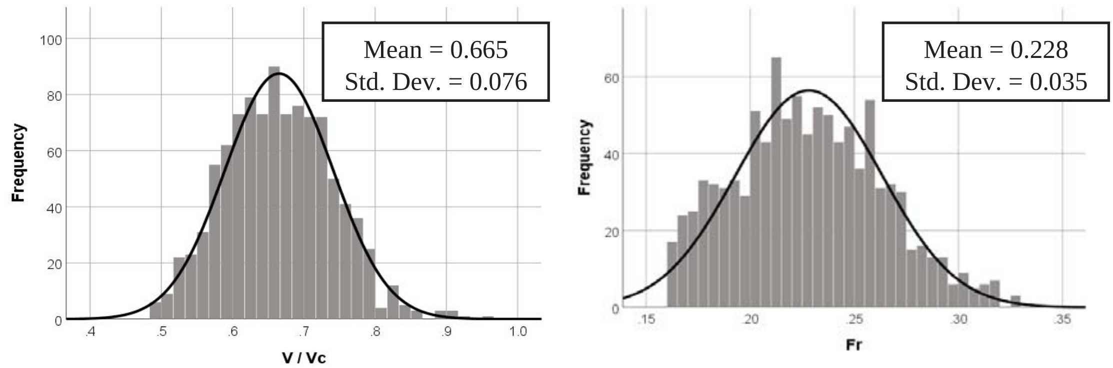


Figure 6: Observation iteration numbers of local scour values



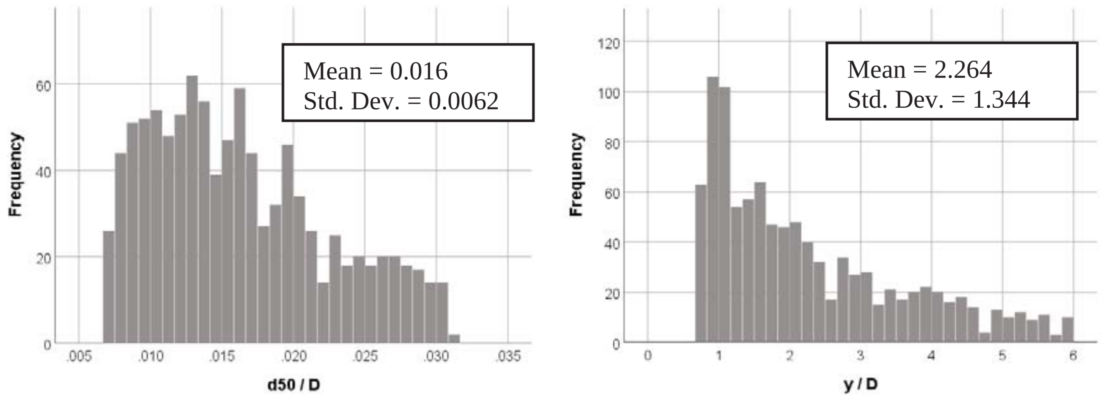


Figure 7: Distribution types of parameters in the equation of local scour (N=1000)

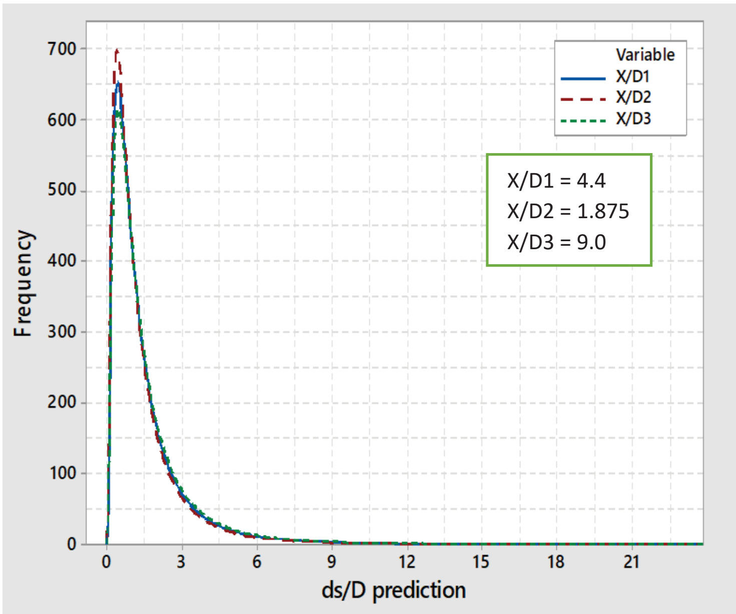


Figure 8: Lognormal distribution of local scour over pier diameter

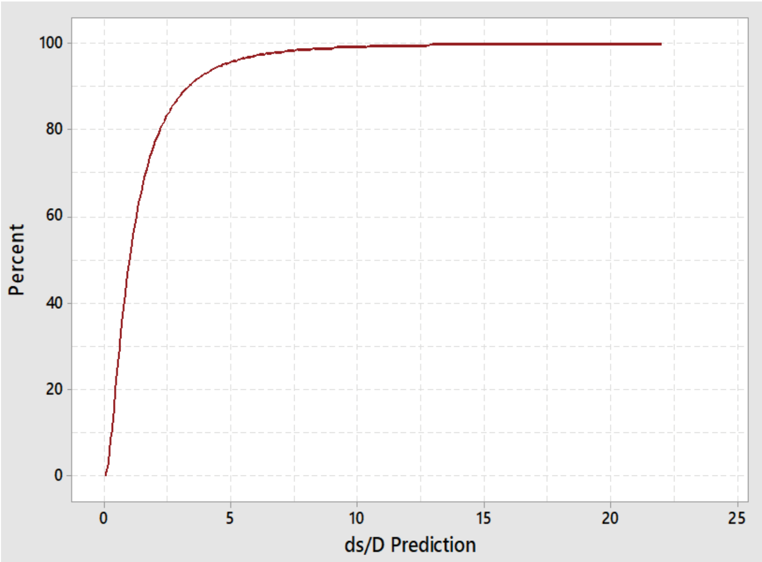


Figure 9: Cumulative probability distribution of local scour values over pier diameter

4. Conclusion

Monte Carlo simulation was used to predict scour around a pier based on lab data in order to test equation reliability. The uncertain variables involved were average velocity, critical velocity, water depth, median bed diameter, and Froude number, while the deterministic variables were the diameter of the pier and the spacing from the pier to the abutment; these were used as input data to estimate local scour. A number of iterations of the Monte Carlo simulation were derived from observation lab data with a suitable number of iterations of simulation for each item derived based on the standard deviation values, giving 1,000 iterations per variable. The distributions of the independent probabilistic variables in the local scour equation were estimated for use in generating the simulation, and the probabilistic variables of the independent observations were distributed as normal and lognormal, with observation data of local scour creating a normal distribution while the lognormal was used for prediction by Monte Carlo simulation. Using the example to check the reliability of the local scour equation showed that the assumed values gave a deterministic value corresponding with a confidence level of 20%, based on the cumulative probability distribution curve. The probabilistic equation is thus a safer option than the deterministic model for computing the local scour around the pier.

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References

[1] Clopper, P., Lagasse, P. F., & Zevenbergen, L. W. (2014). Risk-Based Approach for Bridge Scour Prediction: Applications for Design.
[2] Johnson, P. A., & Dock, D. A. (1998). Probabilistic bridge scour estimates. Journal of Hydraulic Engineering, 124(7), 750-754.
[3] Harrison, L. J., & Morris, J. L. (1991). Bridge scour vulnerability assessment. In Hydraulic Engineering (pp. 209-214). ASCE.
[4] Kamojjala, S., Gattu, N. P., Parola, A. C., & Hagerty, D. J. (1994). Analysis of 1993 Upper Mississippi flood highway infrastructure damage. In Water resources engineering (pp. 1061-1065). ASCE.
[5] Lagasse, P. F., & Richardson, E. V. (2001). ASCE compendium of stream stability and bridge scour papers. Journal of Hydraulic Engineering, 127(7), 531-533.
[6] Karaki, S., & Haynie, R. M. (1963). Mechanics of local scour. Part 2, Bibliography. CER; 63-46.
[7] Heidarpour, M., Khodarahmi, Z., & Mousavi, S. F. (2003, August). Control and reduction of local scour at bridge pier groups using slot. In Thessaloniki, Proc. 30th IAHR Congress (pp. 301-307).
[8] Morales, J. M., & Perez-Ruiz, J. (2007). Point estimate schemes to solve the probabilistic power flow. IEEE Transactions on power systems, 22(4), 1594-1601.
[9] Tubaldi, E., Macorini, L., Izzuddin, B. A., Manes, C., & Laio, F. (2017). A framework for probabilistic assessment of clear-water scour around bridge piers. Structural safety, 69, 11-22.
[10] Johnson, P. A. (1992). Reliability-based pier scour engineering. Journal of Hydraulic engineering, 118(10), 1344-1358.
[11] Abbas R. Oda (2011). Study the Effect of Circular Pier and Abutment on Local Scour Depth. The University of Kufa, college of engineering, civil department, MSc thesis.
[12] Jeng, D. S., Bateni, S. M., & Lockett, E. (2005). Neural network assessment for scour depth around bridge piers. The University of Sydney.
[13] Morales, J. M., & Perez-Ruiz, J. (2007). Point estimate schemes to solve the probabilistic power flow. IEEE Transactions on power systems, 22(4), 1594-1601.
[14] Johnson, P. A., & Ayyub, B. M. (1996). Modeling uncertainty in prediction of pier scour. Journal of hydraulic engineering, 122(2), 66-72.
[15] Murthy, K. P. N. (2001). Monte Carlo: Basics. arXiv preprint cond-mat/0104215.
[16] Nowak, A. S., & Collins, K. R. (2012). Reliability of structures. CRC Press.
[17] Haldar, A., & Mahadevan, S. (2000). Probability, reliability, and statistical methods in engineering design. J. Wiley & Sons, Incorporated.
[18] Husain, A. (2016). Probabilistic study for single pile in cohesionless soil Using Monte Carlo simulation technique. International Journal of Scientific and Engineering Research, 7(2), 628-633.
[19] Helsel, D. R., & Hirsch, R. M. (2002). Statistical methods in water resources (Vol. 323). Reston, VA: US Geological Survey.