Discussing on Prediction of Local Scour Depth of Bridge Foundation

Jin Cao¹, Song Wei²*, Yingjie Zhang², Huadong Chan², and Lingwei Chen²

¹Anhui Transportation holding group Co., LTD., Hefei, Anhui, 230088, P.R.China
²School of Civil and Hydraulic Engineering, HeFei University of Technology, Hefei, Anhui, 230009, P.R. China
³Corresponding author’s e-mail: 910884583@qq.com

Abstract. Local scour is one of the main factors leading to the failure of bridge foundation. In this paper, the mechanism of local scour and various factors affecting local scour are expounded. Based on the erosion mechanism and influencing factors, several common calculating formulas and prediction methods based on calculation algorithm are analysed. Finally, the shortcomings of existing research are summarized and the possible future research directions are pointed out.

1. Introduction
Local scour of bridge pier foundation is one of the main factors of bridge failure. Local scour would cause the sediment near the bridge pier foundation to be eroded by water, which would lead to the decline of bearing capacity of the foundation around the pier and the pier below the overburden layer would be exposed to the flow of water and eroded, which may eventually cause the bridge to be destroyed by water. According to the research results of Shirhole and Holt [1], more than 1,000 bridges collapsed in the United States during the 30 years from 1960 to 1990, and more than 60% of which were related to local erosion of bridge foundations. Yi [2] analyzed the causes of 179 bridge collapse accidents from 2000 to 2014, and found that 32% of the collapse accidents were caused by flood scour. Local scour pit depth of pier is the most important index to evaluate scour hazard. Therefore, it is very important to predict local scour depth accurately.

In this paper, the prediction of local scour depth of bridge foundation is discussed, the mechanism of local scour and its influencing factors are briefly analyzed, the commonly used prediction formulas and prediction methods based on calculation algorithm are summarized, and the existing problems in research and development trend are analyzed.

2. Mechanism of local scour
Local scour of bridge pier is a process of mutual coupling between flow, sediment and bridge pier. The scour mechanism is extremely complex. The present research mainly includes the structure of flow around the pier, the characteristics of sediment movement and the evolution of scour pit.

The flow structure around the pier includes the water surge in front of the pier, the downward flow in front of the pier, the horseshoe vortex formed at the edge of the scour pit in front of the pier that flows downstream around both sides of the pier and the wake vortex caused by the water separation on both sides of the pier [3]. The erosion of these vortices will cause the movement of sediment around the pier. When the velocity of flow exceeds the starting velocity of the sediment, the sediment will
start and be transported downstream by the flow, and the erosion phenomenon will appear on both sides of the pier. With the development of scour, vortex system structure gradually develops in the leading edge of bridge pier and shifts to both sides driven by water flow, and scour gradually develops through the front edge from both sides [4]. As the scour continues, the scour pit depth deepens gradually until it reaches equilibrium, the sediment in the scour pit will no longer start, and it will be in the critical equilibrium state.

3. Influence factors
A large number of studies have shown that there are many complicated factors affecting the local scour of piers, including water depth, velocity, sediment type, shape and size of piers, etc. According to the research and summary of relevant scholars, it can be concretely summarized as the following aspects [3, 5-6].

(1) Flow characteristics: the fluid bulk density, fluid operating viscosity and gravity acceleration, etc.

(2) Channel characteristics: channel width, section shape, hydraulic gradient and roughness, etc.

(3) Bed quality characteristics: sediment bulk density, median particle size, non-uniformity coefficient of sediment particle size, angle of repose and cohesion, etc.

(4) Flow characteristics: traveling current depth, traveling velocity and Froude number, etc.

(5) Pier characteristics: pier width, length, pier shape coefficient and the intersection angle between pier and water flow, etc.

4. Estimation of local scour depth

4.1 Calculation formula of local scour depth

According to local scour mechanism of bridge pier and related influencing factors, many scholars have established a large number of calculation formulas to predict scour depth through field measured data and laboratory test results. For example, Jain and Fischer [7] proposed the maximum clean water scour prediction formula, Melville [8-9] proposed the scour equation based on the envelope curve and its improved formula, Lim [10] proposed the abutment scour equation perpendicular to the direction of water flow, the 65-1 modified formula and 65-2 formula in the Code for Survey and Design on Hydrology of Railway Engineering was proposed by the Ministry of Railways of the People’s Republic of China [11], the formula of HEC-18 recommended by the Federal Highway Administration of the United States [12], Ataie-Ashtiani and Beheshti [13] proposed the calculation formula to predict the local maximum scouring depth of pile group. At present, there are several commonly used.

(1) HEC-18

\[
\frac{y_s}{y_1} = 2.0K_1K_2K_3 \left( \frac{a}{y_1} \right)^{0.65} \frac{1}{Fr_1^{0.43}}
\]

The HEC-18 formula has the same dimension at both ends and can calculate the scour depth of complex piers, but it ignores the influence of sediment particle size distribution and calculates the scour depth to be relatively large.

(2) 65-1 modified formula and 65-2 formula

**65-1 modified formula**

\[
h_b = \begin{cases} 
    k_v \kappa \eta_1 b^{0.6} h_p^{0.15} \frac{v-v_0}{v_0}, & v \leq v_0 \\
    k_v \kappa \eta_1 b^{0.6} (v_0 - v) \left( \frac{v-v_0}{v_0-v_0} \right)^{n_1}, & v > v_0 
\end{cases}
\]

**65-2 formula**

\[
h_b = \begin{cases} 
    k_v \kappa \eta_2 b^{0.6} h_p^{0.15} \frac{v-v_0}{v_0}, & v \leq v_0 \\
    k_v \kappa \eta_2 b^{0.6} h_p \left( \frac{v-v_0}{v_0} \right)^{n_2}, & v > v_0 
\end{cases}
\]
In the scour calculation, many parameters are needed, and most of them have strong uncertainty. Moreover, the dimensions of the formula are discordant. These factors lead to the formula has strong empiricism and with a relatively large limitation. But, the fitting effect between these two formulas and the measured data is better.

(3) Melville formula
Melville and Sutherland [8] proposed a formula to calculate the erosion depth based on the envelope curve drawn from laboratory test data. The initial form of the equation is:

$$\frac{h_s}{L} = K_sK_aK_yK_{1/4}K_\sigma$$  \hspace{1cm} (4)

Later, Melville [9] based on the influence mode of relevant factors and experience summary, compounded the water flow strength and pier width together to replace the water depth coefficient in the original formula. The prediction of local scour depth by Melville formula is obviously on the high side, and the values calculated in laboratory tests and field measurements are relatively conservative.

The above formulas are based on laboratory test results and field data, and the calculation results are better for certain characteristics. However, the field scour is more complicated than the laboratory simulation, and the determination of some influencing factors has greater experience and limitation. Therefore, when selecting these formulas to predict the local scour depth, most of them are inaccurate, and the predicted scour depth is deeper than the real situation.

4.2 Prediction of local scour depth based on computational algorithm
Due to the complicated mechanism of local scour, the results predicted by the existing formulas are not completely reasonable, and the calculation results are quite different and only applicable to some single data sets. Therefore, the traditional method of physical analysis needs to be improved. With the development of computational algorithms, many scholars have applied these algorithms to local scour depth prediction. The application of Neural Network and Support Vector Machine (SVM) in local scour prediction is summarized as follows.

(1) Neural Network
Neural network is a flexible semi-parametric regression method. A significant advantage of neural network prediction of bridge scour is that there is no need to have a clear physical relationship between the scour output of the bridge and various factors affecting the scour input of the bridge [14]. Because neural networks have more freedom in defining the relationship between bridge scour and various factors, they are more accurate in predicting bridge scour depth.

Bateni et al. [15] used artificial neural network (ANNs) and adaptive neuro-fuzzy inference system (ANFIS), and proposed to estimate the equilibrium and time-dependent scour depth with numerous reliable data base. The experimental results show that the prediction of scouring depth by neural network and neuro-fuzzy method is more accurate than the existing methods.

Zounemat-Kermani et al. [16] presents an alternative to the regression in the form of artificial neural networks, ANNs, and adaptive neuro-fuzzy inference system, ANFIS. Two ANNs models, feed forward back propagation, FFBP, and radial basis function, RBF, were utilized to predict the depth of the scour hole. The numerical results show that the neural network model has better prediction effect.

Cheng and Cao [17] developed and applied a hybrid model of radial basis function neural network (RBFNN), fuzzy logic (FL) and artificial bee colony (ABC) algorithm, named intelligent fuzzy radial basis function neural network inference model (IFRIM), to estimate the possible scouring depth of piers. The results show that the root mean square error and the mean absolute error of IFRIM model are 21% and 14.5% lower than those of other artificial intelligence technologies respectively.

(2) Support Vector Machines (SVM)
Support vector machines (SVM) is a dichotomous model. Its mechanism is to find a hyperplane to segment samples, take interval maximization as the segmentation principle, and finally turn it into a convex quadratic programming problem to solve. At present, some scholars have applied SVM technology to bridge local scour prediction and achieved good results.

Goel and Pal [18] studied the application of SVM in scour prediction of hierarchical control structures. Using existing experimental and field data, they established scouring model based on
support vector machine, and compared it with the empirical relationship and back propagation neural network method proposed by others. The results show that the model based on SVM has good practicability. In addition, compared with the other two methods, SVM technology is effective in extending the results from laboratory to field for scour prediction.

Zhang et al. [19] integrated the feature system implementation algorithm and SVM to identify the scour depth of the bridge under the condition of environmental excitation. The results show that the era-based and svm-based scour damage identification method can accurately identify the scour depth of the substructure (water) by using the superstructure's measureability.

Sharafi [20] et al. established support vector machine algorithm (SVM) to predict the scour depth around bridge piers by using six kernel functions. The Y-series prediction results of SVM polynomial are compared with those of ANN, ANFIS and nonlinear regression-based methods. The results show that SVM polynomial has higher accuracy and smaller error in predicting scouring depth.

The application of NN and SVM model in local scour prediction makes the local scour prediction more accurate, and makes up for some shortcomings of traditional prediction methods. However, the prediction results of neural network are less accurate than those of support vector machine, while the results of support vector machine model under the training condition of small samples are better, but it is difficult to model and predict large-scale data samples.

In summary, many scholars have made beneficial research and exploration on the formation, development and application of local scour calculation formulas and local scour prediction models based on calculation algorithm, which can be applied to engineering practice under certain conditions. However, neither of them can reveal the potential scouring mechanism well. In addition, both of them are based on experimental data and field measured data. These data can not cover all kinds of actual scouring situations, and field measured data may not be completely accurate. Therefore, it has great limitations in practical application.

5. Conclusion
In this paper, the research status of prediction of local scour depth of piers is summarized, the research results of local scour mechanism of piers are expounded, the factors affecting local scour of bridge piers are summarized, and several common calculation formulas and methods of local scour depth prediction of bridge piers based on calculation algorithm are analyzed.

In view of the current research on prediction of local scour depth of piers, the following problems and future research trends are put forward:

(1) At present, many formulas are put forward to estimate the local scour depth from the aspects of hydraulics, sediment mechanics and pier structure. In the future, more complex realistic conditions need to be accurately simulated in the laboratory, so as to further analyze the coupling relationship among various influencing factors.

(2) Most of the formulas used to predict the scour depth of bridges are suitable for certain data sets under certain laboratory or field conditions, which has great limitations. Therefore, the establishment of general formula is also the focus of future research.

(3) Developing advanced computational algorithms and models for studying erosion mechanism and predicting erosion is one of the trends of future research.

6. Acknowledgement
This research was financially supported by Anhui Transportation holding group Co., LTD. science and technology project "Evaluation and protection measures of bridge foundation erosion in Anhui Province" (NO. 2017010650), National Natural Science Foundation of China (NO. 51579063) and National Innovation and Entrepreneurship Training Program for College Students (NO. 201810359029).
References

[1] Shirhole, A.M., Holt R.C. (1991) Planning for a comprehensive bridge safety program. Transportation Research Record No. 1290, Transportation Research Board, National Research Council, Washington, D.C.

[2] Yi R.Y., Zou R.F, Huang Q. (2015) Reason and Risk of Bridge Collapse in Recent 15 Years. J. Transportation Science &Technology, 272(5): 61-64.

[3] Jiang S.H., Hou J.G, He Y.M, etc. (2018) Incipient motion of riprap in bridge scour hole by horseshoe vortex. J. Journal of Sediment Research, 43(1): 73-80.

[4] Qi M.L., Shi P.C. (2018) Study on the mechanism of water-sediment interaction in the scouring process around a pile. J. SHUILI XUEBAO, 49(12): 37-46.

[5] Barbhuiya A.K., Dey S. (2004) Local scour at abutments: A review. J. Sadhana, 29(5): 449-476.

[6] Xue X.H. (2005) Experiment Research on the Scour about the Bridge Per. Wuhan University.

[7] Jain S.C., Fischer E.E. (1979) Scour around bridge piers at high Froude numbers. Rep. No. FHWA-RD-79-104, Federal Highway Administration, Washington D.C.

[8] Melville BW, Sutherland AJ. (1988) Design Method for Local Scour at Bridge Piers. J. Journal of Hydraulic Engineering, 114(10): 1210-1226.

[9] Melville BW. (1997) Pier and Abutment Scour: Integrated Approach. J. Journal of Hydraulic Engineering, 123(2): 125–136.

[10] Lim, S.Y. (1997) Equilibrium clear-water scour around an abutment. J. Hydraul. Eng., 123: 237–243.

[11] Ministry of Transport of the People’s Republic of China (2015) Hydrological specifications for survey and design of highway engineering. JTG C30-2015, Beijing, China (in Chinese).

[12] Richardson E.V, Davis S.R. (2012) Evaluating scour at bridges, 5th Ed. Hydraulic Engineering Circular No. 18 (HEC-18), Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

[13] Ataie-Ashtiani B, and Beheshti A.A. (2006) Experimental investigation of clear-water local scour at pile groups. J. Hydraul. Eng., 132(10): 1100–1104.

[14] Deng L., Cai C.S. (2010) Bridge Scour: Prediction, Modeling, Monitoring, and Countermeasures Review. J. Practice Periodical on Structural Design and Construction, 15(2): 125-134.

[15] Bateni S.M, Borghesi S.M, Jeng D.S. (2007) Neural network and neuro-fuzzy assessments for scour depth around bridge piers. J. Engineering Applications of Artificial Intelligence, 20(3): 401-414.

[16] Zounemat-Kermani M., Beheshti A.A., Ataie-Ashtiani B, et al. (2009) Estimation of current-induced scour depth around pile groups using neural network and adaptive neuro-fuzzy inference system. J. Applied Soft Computing, 9(2): 746-755.

[17] Cheng M.Y., Cao M.T. (2015) Hybrid intelligent inference model for enhancing prediction accuracy of scour depth around bridge piers. J. Structure & Infrastructure Engineering, 11(9): 1178-1189.

[18] Goel A., Pal M. (2009) Application of support vector machines in scour prediction on grade-control structures. J. Engineering Applications of Artificial Intelligence, 22(2): 216-223.

[19] Sharaﬁ H., Ebtehaj I., Bonakdari H., et al. (2016) Design of a support vector machine with different kernel functions to predict scour depth around bridge piers. J. Natural Hazards, 84(3): 2145-2162.

[20] Zhang X.Z., Sun Y.H., Sun G.M., et al. (2016) Identification Method of Scour Depth for Bridge Based on ERA and SVM. J. Journal of Water Resources and Architectural Engineering, 14(3): 206-210.