Evaluation of Local Scour Calculation Equations for Bridge Piers in Sandy Riverbed

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Abstract. Local scour depth is the key index of foundation design of bridge across river. At present, there are many equations to calculate the scour depth of bridge piers, but the results of different equations vary greatly. It is still a difficult problem for bridge designers how to choose the appropriate equation for calculating local scour depth. Six typical equations for calculating local scour depth were selected to compare and analyze the influences of pier width, velocity, water depth in front of piers and bed sand particle size on the local scour depth. The results showed that bed sand particle size and geometric non-uniformity coefficient had the most significant influence on the scour depth. It was proposed that the prediction equation should be selected according to the size range and uniformity of bed sand.

Keywords: Bridge piers; local scour; grain size of bed sand; geometric non-uniformity coefficient; calculation equation.

1. Introduction
According to statistics, local scour of bridge piers is one of the main reasons for the water damage of bridges across the river [1]. In the design of bridges, it is an effective measure to predict the scour depth of bridge pier and determine the reasonable buried depth of foundation. In order to predict the scour depth of bridge foundation, many scholars have carried out extensive research work by means of measured data analysis, model test and numerical simulation, and put forward calculation equations of local scour depth under various conditions. However, due to the complexity of water flow structure, sediment start-up conditions and local scour conditions, the calculation results of different equations were quite different [2]. Therefore, how to select and apply the equation according to the actual engineering situation is an urgent problem that bridge engineers need to solve before design.

Some scholars have conducted comparative studies on local scour equations and reached meaningful conclusions [3-13]. However, only a few equations for calculating local scour depth were compared, not including the latest research results in recent years, and no consensus research conclusions have been reached. In this paper, six typical calculation equations were selected to compare and analyze the main factors affecting the local scour depths. The suggestion of selecting the corresponding equation according to the size range and uniformity of bed sediment was presented.
2. Local Scour Calculation Equation of Bridge Piers

2.1. Selection of Calculation Equation
At present, there are many equations to predict the local scour depth of piers under the condition of non-viscous soil riverbed. After years of research and many modifications, some equations have been applied in engineering practice as normative equations. For example, 65-2 and revised 65-1 equations in the Chinese specification (JTG C30-2015) [9], HEC-18 equation in the American specification[10], and Melville equation in the New Zealand specification [11].

In recent years, on the basis of abundant experimental and measured data, some scholars have put forward some new equations that were in good agreement with the measured values, such as Sheppard-Melville equation [12] and Liang equation [13]. These six typical equations were selected to calculate and compare the local scour depths.

2.2. Equations in Chinese Specification
65-2 and revised 65-1 equations were obtained based on the analysis of years of measured data and are widely used in the calculation of local scour depth of piers in China. In the new specification of 2015, the application scope of revised 65-1 equation was supplemented [9]. The specific equations are as follows:

65-2 equation:
\[
h_b = \begin{cases} 
K \times Y \times B \times Y \times F \times \frac{v - V}{V_0} & \text{if } V \leq V_0 \\
K \times Y \times B \times Y \times F \times \frac{v - V_0}{V_0} & \text{if } V > V_0
\end{cases}
\]

Revised 65-1 equation:
\[
h_b = \begin{cases} 
K \times Y \times B \times Y \times F \times \frac{v - V}{V_0} & \text{if } V \leq V_0 \\
K \times Y \times B \times Y \times F \times \frac{v - V_0}{V_0 - V_0} & \text{if } V > V_0
\end{cases}
\]

2.3. HEC-18 Equation
Richardson and Davis et al. developed the equation for predicting the local scour depth of piers, which is also recommended by the Federal Highway Administration and is commonly known as the HEC-18 equation [10].
\[
h_b = 2 \times K_1 \times K_2 \times \left( \frac{B}{h} \right)^{0.45} \times F^{0.45}
\]

2.4. Melville Equation
Melville and Sutherland established the Melville equation based on the envelopment curve method through the analysis and statistics of the pier scouring test data [11].
\[
h_b = K \times K \times K \times K \times K
\]

2.5. Sheppard-Melville Equation
Sheppard and Miller refined the flow velocity conditions on the basis of Melville equation and obtained the Sheppard-Melville equation (S-M for short) [12].
\[
h_b = \begin{cases} 
2.2 f_v \times f_v \times \frac{v - V}{V_0} & \text{if } 0.4 \times \frac{v - V}{V_0} \leq 1.0 \\
2.2 f_v \times f_v \times \frac{v - V}{V_0} & \text{if } 1.0 \times \frac{v - V}{V_0} \leq \frac{v}{V_0}
\end{cases}
\]
2.6. Liang Equation
Liang et al. summarized a prediction equation for local scour depth of bridge piers on the basis of experimental research [13].

\[ h_b = 1.13K_{m0}K_uK_p h_0^{0.698} d_{s0}^{-0.114} B_1^{0.416} F_r^{0.42} \]  \( \text{(6)} \)

3. Analysis of scour depth calculated by typical formulas under the influence of different factors

3.1. Parameters Selection
Local scour of piers is the result of the interaction among water flow, structure and sediment. Although the above six equations have different expressions, they all include the parameters such as sediment particle size, flow velocity, water depth and pier width. Five parameters including sediment particle size, geometric non-uniformity coefficient, flow velocity, water depth and pier width were selected in this paper. Taking a single cylindrical bridge pier in a rectangular flume with a width of 2 m as an example, the influencing factors of the calculated scour depth were analyzed. The specific calculation conditions were shown in Table 1. The heterogeneity of sediment is expressed by geometric heterogeneity coefficient \( \sigma_g = \frac{d_{16}}{d_{50}} \). When \( \sigma_g \leq 1.4 \), the sediment is uniform. While \( \sigma_g > 1.4 \), it means that the sediment is non-uniform. Due to the complexity of the impact of sediment particle size on the scour depth, the influence curves of pier width, water depth and flow velocity on local scour depth under different sediment particle size were comprehensively drawn, as shown in Fig. 1-3.

Table 1. Parameters range of local scour depth calculation

| Group Number | Sediment Particle Size \( d_s \) (mm) | \( \sigma_g \) | Depth \( h \) (m) | Flow Velocity \( v \) (m/s) | Pier Width \( B_1 \) (m) |
|--------------|-------------------------------------|--------------|-----------------|-------------------|-----------------|
| 1            | 0.2-30.00                           | 1.00         | 0.50            | 0.50              | 0.08            |
| 2            | 0.62                                | 1.00         | 0.50            | 0.50              | 0.08            |
| 3            | 0.2-30.00                           | 0.20-2.00    | 0.50            | 0.08              | 0.08            |
| 4            | 0.2-30.00                           | 0.50         | 0.10-2.00       | 0.08              | 0.08            |
| 5            | 0.2-30.00                           | 0.50         | 0.01-0.90       | 0.08              | 0.08            |

Note: The mean sediment particle size \( d_\bar{\bar{d}} \) and median particle size \( d_{50} \) in the equation are collectively called sediment particle size \( d_s \).

3.2. Scour Depth Analysis Considering Pier Width
Fig. 1 showed the influence of pier width on the calculation results of the six formulas under the condition of the same particle size. On the whole, the local scour depths increased with the pier width, but the increase amplitudes were slightly different.
The influences of particle size on local scour depth at the same pier width were also shown in Fig. 1. The local scour depths calculated by 65-1, revised 65-2 and Liang equations decreased with the increase of particle size. When $d_s > 10$ mm, both the scour depth calculated by 65-2 and revised 65-1 equations were less than zero. The calculation results of HEC-18 equation do not change with particle size. But when $B_s > 0.6$ m, the curve was divided into three routes according to the range of particle size due to the wide pier correction. When $d_s \leq 1$ mm, the calculation results of Melville equation did not change with particle size, while results of S-M equation increased with particle size. However, the scour depths calculated by Melville and S-M equations decreased with the increase of particle size when $d_s > 1$ mm. The scour depths of S-M equation were zero when the sediment particle sizes exceeded 20 mm.

3.3. Scour Depth Analysis Considering the Water Depth

Fig. 2 depicted the variation of the calculated scour depth with the water depth. Under the condition of the same particle size, the local scour depths calculated by the Liang and HEC-18 equations increased with the water depth. The revised 65-1 and Melville equations both decreased with the increase of water depth. The variation trend of 65-2 and S-M equations with water depth were complex. The variation trends were different in different particle size ranges. When the particle size was small, the scour depth increased with the water depth, but decreased gradually when it was large. The influence rules of particle size on local scour depth under the same water depth shown in Fig. 2 were exactly the same as that shown in Fig. 1.

![Fig. 1 Influence of pier width on local scour depth under different particle sizes. a Revised 65-1; b 65-2; c HEC-18; d Melville; e S-M; f Liang.](image)

![Fig. 2 Influence of water depth on local scour depth under different particle sizes: a Revised 65-1; b 65-2; c HEC-18; d Melville; e S-M; f Liang.](image)
3.4. Scour Depth Analysis Considering the Velocity
The variations of local scour depths with flow velocity were shown in Fig. 3. Under the condition of the same particle size, the local scour depth calculated by each equation increased with the velocity. However, the increase tendencies with the velocity were not the same. The scour depths of Melville equation increased to stable values. The curve of the relationship between the result of HEC-18 equation and the velocity was step-shaped. When the velocity was small, the scour depths calculated by revised 65-1 and 65-2 equations would be less than zero.

Fig. 3 depicted the influence rule of particle size on local scour depth at the same velocity. It was similar to those shown in Fig. 1 and 2.

3.5. Scour Depth Analysis Considering the Sediment Non-uniformity
Natural sediments in actual riverbeds are usually uneven. For non-uniform gravel riverbed, the effect of coarsening should be considered. With the median particle size of sediment, water depth, flow velocity and pier width unchanged, the variation curve of scour depths with the sediment inhomogeneity coefficients were shown in Fig. 4.

Fig. 4 Influence of sediment non-uniformity on local scour depth.

When the non-uniformity coefficient increased, the scour depths calculated by 65-1 and 65-2 equations gradually decreased. However, it had no obvious influence on the calculation depth of HEC-18, Melville, S-M and Liang equations.

4. Summary and Conclusions
Six typical equations were selected to study the influence rules of sediment particle size, velocity, water depth and pier width on the calculated local scour depths of bridge piers. The analysis indicated that the
influences of pier width and flow velocity on scour depths were the same. However, there were some differences in the influence laws of water depth on scour depth.

Under the same conditions of pier width, velocity or water depth, the influence laws of sediment particle size and non-uniformity coefficient on scour depths were obviously different. In the revised 65-1, 65-2 and S-M equations, the effects of the sediment particle size were significant. It should be noted that under coarse sediment conditions ($d_{90} > 20$ mm), the scour depths calculated by revised 65-1 and 65-2 equations were less than zero, and the scour depths calculated by S-M equation were equal to zero. Moreover, the non-uniformity coefficient significantly affected the calculation results of the revised 65-1 and 65-2 equations. Therefore, it was suggested to select local scour depth prediction equations according to the different size range and uniformity of sediment. The specific range and method of equations selection need further research.

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