Analysis of the Influence of Bridge Piers on River Flow-Scouring Calculation

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Abstract. Many bridges collapsed due to the affection of flow, among which scouring has become one of the critical reasons that leads to flow-caused bridge damages and accidents, therefore the analysis of pier scour is of great benefit for the safety assessment of bridge engineering. Newly constructed bridges on the Fuhuan River, a tributary of the Yangtze River, are selected as the object of study. The scouring effect of flow on the bridge piers are evaluated, as shown in the calculation results, the existing design scheme can meet the bridge safety requirements.

1. Introduction

After the bridge is built, Scouring swirls are generated near the bed due to the obstructive effect of the bridge, which in turn causes bridge pier erosion. As one of the main causes of bridge damage due to flow affection, according to incomplete statistics, the underestimation of the bridge erosion caused the 60% of all unintended damaged bridge[1] Therefore, the computational analysis of bridge pier scour played an important role in assessing bridge safety.

Many theoretical studies are made on bridge scour, such as the HEC-18[2] adopted by the U.S. Department of Transportation, which suggests that the total under-bridge scour is consisted of riverbed scour and silt, narrow riverbed scour, and local scour. China's bridge pier scour calculation code [3] regulated that bridge pier scour is consisted of general scour and local scour. According to Kan Yi [4], the flow swirls and rolls near the piers, forms a complex, vortex bands that rotating outwards of the piers, i.e., horseshoe vortex. Shen et al [5] concluded that the rolling at the unstable shear layer on the surface of the bridge forms the tail vortex.

The predicted bridge is located on the Fuhuan River, a tributary of the Yangtze River, with the left bank a high elevation ground at where the bridge spans, and the right bank the East-West Lake embankment. A (75+135+75) m continuous beams are adopted to span the main channel of the Fu River, within the riverbank area. 30 m or 25 m of simple-supported beams are adopted, the 9.6m wide bridge spans a total length 895m across the river bank and the main channel with 21 piers; the main span 80m is predicted to span the East West Lake embankment.

According to the actual situation of the project and to the "Specifications for Survey and Design of Highway Bridge Site", the pier scour is studied, the most unfavourable combination of scouring is taken into consideration and local scouring was used as a result of scouring calculations [3].
2. Calculation formulas

According to the riverbed geological data at the bridge crossing, the thickness of clay and silty clay overlying the main channel is about 5-20m, and the thickness of the overlying plain, silty clay and clay overlying the side beach is about 15-25m. Therefore, the depth of scour pit is calculated according to clay soil.

(1) General scouring formula

According to the “Hydrological Specifications for Survey and Design of Highway Engineering” (JTG C30-2015), the general scour formula of the cohesive soil riverbed is as follows.

1) In the river channel

\[
h_p = \left[ \frac{I_L}{0.33} A_d \frac{Q_r}{\mu B_{ij}} \left( \frac{h_{in}}{h_{iq}} \right)^{\frac{5}{7}} \right]^{\frac{6}{7}}
\]

Where:
- \(h_p\) is the maximum water depth (m) after general scouring under the bridge.
- \(Q_r\) is the design flow rate \(m^3/s\) at a frequency of \(P\%\).
- \(Q_1\) design flow \(m^3/s\) for the channel portion passing under the bridge, \(Q_1\) is taken when the channel can be widened to the full bridge;
- \(Q_2\) is the design flow \(m^3/s\) of the channel section in natural conditions.
- \(\mu\) is the lateral compression coefficient of the abutment water flow and shall be determined in accordance with Table 1. \(B_{ij}\) is the net width (m) of some of the bridge bore crossings when the channel under the bridge is widened to the full bridge, i.e., the net width of all bridge bore crossings.
- \(h_{in}\) is the maximum water depth of the river channel (m);
- \(h_{iq}\) is the average water depth in the channel under the bridge (m).
- \(A_d\) is single-width flow concentration coefficients, ranging from 1.0 to 2.0. \(I_L\) is an index of the liquidity of the clayey soil within the scouring pit. The scope of application is \(I_L = 0.16 \sim 1.19\).

| Design flow velocity \(v_1\) (m/s) | Net span of single hole \(L_0\) (m) |
|-----------------------------------|----------------------------------|
| \(\leq 10\)                       | 13 16 20 25 30 35 40 45          |
| <1                                | 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 |
| 1.0                               | 0.96 0.97 0.98 0.99 0.99 0.99 0.99 0.99 |
| 1.5                               | 0.96 0.96 0.97 0.97 0.98 0.98 0.98 0.99 |
| 2.0                               | 0.93 0.94 0.95 0.97 0.97 0.98 0.98 0.98 |
| 2.5                               | 0.90 0.93 0.94 0.96 0.96 0.97 0.97 0.98 |
| 3.0                               | 0.89 0.91 0.93 0.95 0.96 0.96 0.97 0.98 |
| 3.5                               | 0.87 0.90 0.92 0.94 0.95 0.96 0.96 0.97 |
| \(\geq 4.0\)                      | 0.85 0.88 0.91 0.93 0.94 0.95 0.96 0.96 |

When the net span of a single width is \(L_0 > 45\), it can be calculated according to \(\mu = 1 - 0.375v_1/L_0\). For bridge holes of unequal span, the average value of \(\mu\) for each hole can be used. When the net span of a single hole is greater than 200m, \(\mu \approx 1.0\).

2) On the Riverbank

\[
h_p = \left[ \frac{I_L}{0.33} A_d \frac{Q_1}{\mu B_{ij}} \left( \frac{h_{in}}{h_{iq}} \right)^{\frac{5}{7}} \right]^{\frac{6}{7}}
\]
where: \( Q_i \) is the design flow rate (m\(^3\)/s) through the river bank under the bridge; \( h_m \) is the maximum water depth (m) of the river bank under the bridge; \( h_{av} \) is the average water depth (m) of the river bank under the bridge; \( \beta_i \) is the net length (m) of the hole of the river bank part of the bridge.

(2) Local scour calculation formula

The local scour of bridge piers on the cohesive soil riverbed is calculated according to the following formula [3]:

\[
\frac{h_p}{B_i} \geq 2.5, \quad h_p = 0.83K_x B_i^{0.6} I_L^{1.25} \sqrt{v} \quad (3)
\]

\[
\frac{h_p}{B_i} < 2.5, \quad h_p = 0.55K_x B_i^{0.6} h_p^{0.1} I_L^{1.0} \sqrt{v} \quad (4)
\]

In the formula, \( L \) is the liquidity index of the cohesive soil sample in the erosion range, and the range is 0.16-1.48; \( h_p \) is the local scouring of the pier. depth (m); \( K_x \) is the pier form factor; \( B_i \) is the calculated width of the pier (m); \( h_p \) is the maximum water depth (m) after general scour; \( V \) is the Travel velocity (m/s) in front of the pier after general erosion.

3. Calculation conditions

(1) Hydrological conditions

Consider the most unfavourable water flow conditions from the point of view of bridge safety, the flood control design flood conditions was selected for calculation and analysis of bridge pier scour.

1) Flood control design flow

Due to the mutual influence of inland river flood and outer river flood, the design standard of the section below Wolongtan of Fuhuan River needs to be determined through comprehensive analysis. The design flood standard of the section from Wolongtan to Daijiashan of Fuhuan River adopts the outsourcing line of the highest flood level of the Yangtze River in 1954 encountered the five-year inflow of the inland river, and the 1996 flood of the Fuhuan River.

Table 2. Calculated hydrological conditions of the Fuhan River.

| cross-sectional stake number | location     | The 1996-type floods | The combination of the water level of the outer river in 1954 and the five-year inflow of the inland river |
|-----------------------------|--------------|----------------------|--------------------------------------------------|
| 62+389                      | Wolongtan (m\(^3\)/s) | 6190                 | 3560                                             |
| 33+668                      | Jiehekou (m\(^3\)/s)  | 5571                 | 3204                                             |
| 12+147                      | Houhu Estuary (m\(^3\)/s) | 5447                | 3133                                             |
| 9+674                       | Daijiashan (m)      | 26.35                | 27.67                                            |

Hubei Institute of Water Resources Survey and Design compiled "The Feasibility Study Report on the Rehabilitation and Reinforcement Projects of Fuhuan Dike and Jushui Dike of the Yangtze River Branch in Wuhan" in 2003 [6]. According to the report, in 1996, the measured maximum water level of Wolongtan of Fuhuan river was 28.58m, corresponding to the maximum peak discharge of 6190m\(^3\)/s, and the corresponding water level of the outer river at the outlet was 28.08m. The reduction coefficient of the peak discharge along the section is as follows: from Wolongtan to the Wangmu estuary the attenuation coefficient is 0.98, from the Wangmu estuary to Sanchahe estuary the attenuation coefficient is 0.95, from the Sanchahe estuary to the Jiehekou the attenuation coefficient is 0.90, and 0.88 from the Jiehekou to the Houhu estuary. The calculated hydrological conditions are shown in Table 2.

The location of the proposed bridge is located between the Jiehekou and the Houhu estuary, and it is estimated that the 1996-type flood flow corresponding to the location of the proposed project is about
5570 m³/s; The combination of the water level of the outer river in 1954 and the five-year inflow of the inland river is about 3200 m³/s.

2) Flood protection design flood

According to "The Feasibility Study Report on the Rehabilitation and Reinforcement Projects of Fuhuan Dike and Jushui Dike of the Yangtze River Branch in Wuhan" [7], the flood level at the proposed bridge location is 27.798 m.

(2) Other condition

According to the engineering design data, the cross-sectional layout of the proposed bridge is taken as the calculation condition, the total length of the section is about 900 m, with about 21 piers in total, and the scour calculation diagram is shown in Figure 1 (from the north bank to the south bank).

In the absence of measured data to determine the validation roughness ratio, reference [7], the roughness ratio of the main channel was taken as 0.03, and the roughness ratio of the beach was taken as 0.038-0.043.

4. Calculation results

According to equation (1)-equation (4), the calculation results of the scouring depth of the proposed bridge are shown in Table 3. Under the conditions of the 1996 type flood flow (Case 1), the maximum erosion depth of the bridge piers in the main trough of the proposed bridge is 3.44 m, and the maximum erosion depth of the bridge piers on the beach is 0.62 m. Under the combined conditions of the water level of the outer river in 1954 and the five-year inflow of the inland river (Case 2), the maximum erosion depth of the bridge piers in the main trough is 2.32 m, and the maximum erosion depth of the bridge piers on the beach is 0.50 m.

| Serial number | Pier diameter (m) | General scour (m) | Partial scour (m) | Total scour depth (m) | General scour (m) | Partial scour (m) | Total scour depth (m) | Position |
|---------------|-----------------|------------------|------------------|----------------------|------------------|------------------|----------------------|----------|
| 1             | 1.6             | 0.08             | 0.34             | 0.42                 | 0.03             | 0.30             | 0.33                 | North Shore Beach |
| 2             | 1.6             | 0.08             | 0.34             | 0.42                 | 0.03             | 0.30             | 0.33                 |          |
| 3             | 1.6             | 0.08             | 0.34             | 0.42                 | 0.03             | 0.30             | 0.33                 |          |
| 4             | 1.6             | 0.08             | 0.34             | 0.42                 | 0.03             | 0.30             | 0.33                 |          |
5. Conclusion

The empirical formula method is used to calculate the scour of the bridge across the Fuhuan River, and the scour law of the pier at the beach and channel is studied. The results show that, under the two calculation conditions, the thickness of the overlying clay and silt clay at the span of the proposed project is greater than the scour depth value. Therefore, the maximum depth of the above-mentioned scour does not penetrate the silt layer and the bridge project can be considered safe.

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References

[1] DANIEL I. 2004, Risk assessment of existing bridge structures. Cambridge: University of Cambridge.
[2] ARNESON L A, ZEVENBERGEN L W, LAGASSE P F, et al. 2012, Evaluating scour at bridges, fifth edition. Cambridge: Department of Transportation Federal Highway Administration.
[3] Ministry of Transport of the People’s Republic of China. 2015, Specifications for Survey and Design of Highway Bridge Site (JTG C30-2015).
[4] Yi Kan. Bridge Crossing. 2004, Beijing: China Railway Publishing House.
[5] SHEN H W, SCHNEIDER R V R, KARAHI S S. 1940, Local scour around bridge piers. Journal of the Hydraulics Division. 95(1): 1919-1940.
[6] Hubei Institute of Water Resources Survey and Design. 2003, The Feasibility Study Report on the Rehabilitation and Reinforcement Projects of Fuhuan Dike and Jushui Dike of the Yangtze River Branch in Wuhan.