Analysis of Impacts of Crossing Bridges on Flood Control and Dike Safety

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Abstract: The construction of bridges across rivers mostly involves occupying river sections and dike sections, which will adversely affect flood control of rivers and the safety and stability of dikes. Taking an actual project for example, this paper puts forward some ideas and methods for the analysis of impacts of crossing bridges on flood control and dike safety, analyses and evaluates effects of raising of water level, dike foot erosion, seepage stability and anti-sliding stability. Finally, suggestions and measures for bridge construction and dike protection are raised.

1. Introduction
The crossing bridge is an important project combing transportation and water conservancy. Most of the river-crossing bridges occupy water area, narrowing the water section, causing raising of water level and dike erosion, which adversely affect flood control safety. Some bridge piers occupy river dike sections, which directly affect the safety and stability of the dike. In order to ensure flood control safety, the flood control impact assessment of new bridges across rivers should be carried out. This paper takes an actual project as an example to analyse the impact of bridges across rivers on river flood control and dike safety and stability and proposes preventive measures to mitigate adverse effects.

2. Engineering situation
The total length of the bridge is 622m and the span is 3.5m×35m+(80+140+80) m+4×35m+3.5m. This bridge crosses a mountainous river channel and intersects with the two sides of the flood control dike. Among all the piers, piers from 3# to 8# are located within the channel and 2# pier is located on the right bank dike land-side slope. The plane and facade layout of the bridge is shown in figure 1 and figure 2.
3. Impact analysis of safety

3.1. Impact analysis of water level raising

3.1.1. Computing method

The plane two-dimensional hydrodynamic model is used to analyse the impact of bridge construction on river flooding\(^{(1)}\).

The two-dimensional model uses a two-dimensional shallow water equation set that averages along the water depth, including the water flow continuity equation, the water flow momentum equations along x-direction and y-direction. The form is as follows:

water flow continuity equation:

\[
\frac{\partial z}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = s
\]  

(1)

water flow momentum equation along x-direction:

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( pq \right) + gh \frac{\partial z}{\partial x} + \frac{gp}{h^2 c^2} \Omega q - E \left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right) = s_{ix}
\]  

(2)

water flow momentum equation along y-direction:
\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) + gh \frac{\partial z}{\partial y} + gq \sqrt{\frac{p^2 + q^2}{h^2 c^2}} - \Omega p - E \left( \frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2} \right) = s_{iy} \tag{3}
\]

where: \( z \) is water level; \( p \) and \( q \) are unit discharges along \( x \) direction and \( y \) direction; \( h \) is water depth; \( s \) is the source sink term; \( s_{ix} \) and \( s_{iy} \) are the components of the source sink term along \( x \) direction and \( y \) direction; \( c \) is Chézy resistance coefficient; \( \Omega \) is Coriolis force and \( E \) is turbulent diffusion coefficient.

3.1.2. Result analysis

Through the calculation and analysis of the model, the 20-year water level rising in the bridge site is shown in Table 1. The water level difference before and after the construction of the bridge is shown in Figure 3. According to the result, the water level change is mainly concentrated in the local area near the bridge. To be specific, the water level in the upper reach of the bridge is raised and the raised water level gradually reduces when the distance from the bridge increases, whereas the water level in the downstream is reduced.

The design standard for flood control dike in this section is once in a 20-year. The raising water level generated by the bridge is 0.05m which is within the 10% safe super-elevation of the dike (0.06m). Therefore, the dike elevation can still meet the flood control requirements without the need to raise the dike after the bridge is built.

Table 1. Computation result of raising water level

| Recurrence interval (year) | Water level before bridge construction (m) | Water level after bridge construction (m) | Raising water level (m) | Length of water-raised reach (m) |
|----------------------------|--------------------------------------------|------------------------------------------|------------------------|---------------------------------|
| 20                         | 63.60                                      | 63.65                                    | 0.05                   | 900                             |

Figure 3. Water level difference before and after the bridge construction
3.2. Analysis of dike foot erosion

3.2.1. Computing method

The 3# pier is close to the foot of the dike. Due to the influence of the compressed water flow by the pier, the dike erosion is intensified and the impact needs to be analysed[2,3]. The 3# pier is located in the river beach and the riverbed is mainly composed of non-cohesive soil.

(1) Calculation of general erosion

\[
Q_i = \frac{Q_{e1}}{Q_e + Q_{e1}}Q_p, \quad A = \left(\frac{\sqrt{B}}{H}\right)^{0.15}
\]

where: \(h_p\) is the maximum water depth under the bridge after erosion; \(A_d\) is concentration coefficient of unit discharge; \(B\) is the channel width at the channel-full water level; \(H\) is the average channel water depth at the channel-full water level; \(Q_i\) is the designed discharge through the river shoal under the bridge; \(h_{m}\) is the maximum water depth of the river shoal under the bridge; \(h_{tq}\) is the average water depth of the river shoal under the bridge; \(\mu\) is the lateral compression coefficient of the bridge pier; \(B_{tj}\) is the net length of bridge holes of the river shoal; \(V_{H1}\) is non-scouring flow velocity of non-cohesive soil when the river shoal water depth is 1m; \(Q_p\) is the designed discharge at the frequency of \(P\%\); \(Q_c\) and \(Q_{e1}\) are respectively the designed discharges of the channel and the shoal in the natural state.

(2) Calculation of local erosion

\[
h_b = K_zK_{n2}B_t^{0.69}h_p^{0.15}\left(\frac{V - V_0'}{V_0}\right)^{a_2} \quad V \leq V_0
\]

\[
h_b = K_zK_{n2}B_t^{0.69}h_p^{0.15}\left(\frac{V - V_0'}{V_0}\right)^{a_2} \quad V > V_0
\]

\[
K_{n2} = \frac{0.0023}{d^{2.2}} + 0.375\tilde{d}^{0.24}, \quad V = V_{H1}, \quad h_p^{0.69}V_0 = 0.28(\tilde{d} + 0.7)^{0.5}
\]

where: \(h_b\) is the local erosion depth of the pier; \(K_z\) is the pier shape factor; \(B_t\) is the calculative width of the pier; \(h_p\) is the maximum water depth of general erosion; \(\tilde{d}\) is the average sediment particle size of the riverbed; \(V\) is the flowing velocity in front of the pier after general erosion; \(V_0\) is the incipient velocity of the riverbed sediment and \(V_0'\) is the incipient erosion velocity of the sediment in front of the pier.

3.2.2. Result analysis

The flow velocity value is calculated by the mathematical model. As the input, the flow velocity is applied to the empirical formula to calculate the erosion depths. The general erosion depth is 0.30m and the local erosion depth is 1.25m thus the total maximum erosion depth is 1.55m.
The dike foot depth is 1.0m which is less than the maximum erosion depth. Therefore, protective measures are needed to ensure the safety of the dike. According to the experience, it is necessary to protect the dike within the range of 4-5 times pier width from the pier.

3.3. Analysis of dike seepage stability

3.3.1. Computing method

The 2# pier is located on the land site of the dike and analysis of seepage stability is needed.

As for the stable seepage, it conforms to the non-uniform anisotropy two-dimensional seepage field of Darcy’s law and the head potential function satisfies the differential equation.

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial \varphi}{\partial y} \right) + Q = 0
\]

(6)

where: \( \varphi = \varphi(x,y) \) is the head potential function; \( x \) and \( y \) are plane coordinates; \( k_x \) and \( k_y \) are respectively seepage coefficients along \( x \)-axis direction and \( y \)-axis direction.

Taking the designed flood level stable seepage as the calculation condition, the designed flood level of dike riverside is 63.65m and the water level of landside is 59.99m (0.5m below the ground)\(^4\). In the seepage analysis, the material seepage coefficient refers to the preliminary design data of the dike. In the seepage analysis, the geomembrane is considered to be impervious. The permeability coefficients of the dike materials are shown in table 2.

### Table 2. Permeability coefficients of materials for each part of the dike

| Material                        | Permeability coefficient (cm/s) |
|---------------------------------|---------------------------------|
|                                | Horizontal      | Vertical      |
| Sand gravel filling material    | \(7.0 \times 10^{-3}\)   | \(7.0 \times 10^{-3}\) |
| Geomembrane                    | \(1.0 \times 10^{-12}\) | \(1.0 \times 10^{-12}\) |
| Sand gravel of dike base       | \(7.0 \times 10^{-3}\)   | \(7.0 \times 10^{-3}\) |

3.3.2. Result analysis

Seepage analysis of the dike section before and after the pier is made. The results are shown in figure 4 and figure 5. The detailed view of the seepage affected section is shown in figure 6.

The raising water level is approximately 5cm on the left side of the pier (point A in figure 6) and the dropping water level is approximately 5cm on the right side of the pier (point B in figure 6). The total water head difference between the two sides of the dike is 3.66m. The local raise (or drop) value of the dike’s internal seepage water level caused by the pier is about 1.4% of the total head difference. That is to say the impact on the dike seepage is relatively small.

According to the preliminary report of the dike, the allowed gradient of permeation of sand gravel is 0.1-0.15. according to the result, the maximum permeation gradient of the affected section is about 0.09. Therefore, the seepage stability of the dike in the affected area meets the requirements.

![Figure 4. Seepage analysis results of dike section without bridge pier](image-url)
3.4. Analysis of dike anti-sliding stability

3.4.1. Computing method

The overall stability analysis of the dike is calculated using the Swedish Arc Method. Safety factor for anti-sliding stability during the completion period:

\[
K = \frac{\sum (c_u b \sec \beta + W \cos \beta \tan \phi_u)}{\sum W \sin \beta}
\]

(7)

Safety factor for anti-sliding stability during the water level sudden drop period:

\[
K = \frac{\sum [c_u b \sec \beta + (S \cos \beta - u_i b \sec \beta) \tan \phi_u]}{\sum W \sin \beta}
\]

\[
W = W_1 + W_2 + \gamma_w Zb
\]

(8)

(9)

where: \(K\) is safety factor; \(b\) is soil stripe width; \(W\) is bar gravity; \(W_1\) is bar gravity above the water level outside the dike slope; \(W_2\) is bar gravity below the water level outside the dike slope; \(Z\) is the distance between the water level and the midpoint of the bottom of the bar; \(u\) is pore pressure in the dike or the dike base during stable seepage period; \(u_i\) is pore pressure of the dike before water level fall; \(\beta\) is the angle between the gravity line of the bar and the radius passing through the midpoint of the bottom surface of the bar; \(\gamma_w\) is the gravity of unit volume water; \(C_u, \phi_u, C_{cu}\) and \(\phi_{cu}\) are respectively quick shear and consolidation quick shear strength indices of soil.

The clay is analyzed with the quick shear index and the calculation method is the total stress method\cite{4}. Characteristics of the materials of the dike are shown in table 3.

| Material | Natural bulk density | Saturated bulk density | Shear strength index (quick shear index for clay) |
|----------|----------------------|------------------------|--------------------------------------------------|

Table 3. Material characteristic indices of the dike slope anti-sliding stability analysis
3.4.2. Result analysis
This overall stability calculation mainly reviews the stability of the dike during the construction period. Condition 1: excavation condition of pile foundation; Condition 2: construction condition of pile foundation (considering applying 20kPa construction load on the top of the dike).

The calculation results of the dike slope anti-sliding stability for the standard section under each condition are shown in table 4. According to the results, the safety factor of dike’s anti-sliding stability is greater than the safety factor allowed by the norm. Therefore, the dike anti-sliding stability meets the requirements of the norm[5].

Table 4. Calculation results of the dike’s anti-sliding stability

| Calculation condition | Location       | Safety factor | Allowed safety factor K |
|-----------------------|----------------|---------------|-------------------------|
| condition 1           | landside slope | 2.40          | 1.05                    |
| condition 2           | landside slope | 1.98          | 1.05                    |

Figure 7. Calculation result of condition 1

Figure 8. Calculation result of condition 2
4. Conclusions and suggestions
(1) The raising water level caused by bridge construction is controlled within the 10% safe super-elevation of the dike. Therefore, the levee elevation can still meet the flood control requirements without the need to raise the dike after the bridge is built.

(2) The 2# pier is located on the landside slope of the dike and its construction will excavate the partial slope of the dike and break the integrity of the dike. The riverside slope is the high beach of the river and there is no water flowing usually. The project involving the dike should be arranged in non-flood season and the dike should be repaired before the flood season.

(3) The 3# pier is near to the dike root and the maximum erosion depth is greater than the dike foot depth. Therefore, protective measures are needed to ensure the safety of the dike. According to previous experience, it is necessary to protect the dike within the range of 4-5 times pier width from the pier.

(4) The maximum permeation gradient of the affected area around the 2# pier is less than the allowed one thus the dike seepage stability meets the requirements of the norm. The dike anti-sliding stability safety factor is greater than the allowed one thus the dike anti-sliding stability meets the requirements of the norm.

(5) During the construction, the disturbance and damage to the dike by mechanical vibration and heavy machinery carry. The construction slope protection platform is conducive to the stability of the landside slope. After the completion of the pier construction, it is recommended to retain the slope protection platform, the steel casing and the foundation pit support steel sheet pile. In order to ensure the safety of the dike, monitoring piles should be set to monitor the stability of the dike during construction. Once the problems are found, they should be solved in time.

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