Application Research of Maintenance and Reinforcement Technology for Arch Bridge Foundation

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Abstract. In order to study the application of maintenance and reinforcement technology for arch bridge foundation, taking a reinforced concrete half-through arch bridge and a rigid frame arch bridges as examples, the appearance inspection and disease analysis of the bridge piers and pile foundations were carried out. Based on the modified theoretical calculation model, the analysis method of diseases and the maintenance and reinforcement technology were proposed. The method of the pier section enlargement and adding pile is adopted to strengthen the arch bridge foundation. The results show that according to the modified theoretical calculation model, the actual diseases including the distribution area of cracks and degradation degree are in good agreement with the theoretical calculation results. The reinforcement design of section enlargement and adding pile can provide a reference for the reinforcement of similar arch bridges.

Keywords: Bridge reinforcement, Bearing capacity of piers, Section enlargement method, Adding pile method, Modified theoretical calculation model

1. Introduction
A large number of existing bridges were built with low design load standards, which leads to insufficient bearing capacity and structural damage. Therefore, the assessment and reinforcement of existing bridges are paid more and more attention [1]. Scholars at abroad have carried out a series of discussions on the methods of bridge design, assessment and reinforcement [2–4]. They do a research on the assessment, test and maintenance of in-service bridge structures [5–7]. Corresponding regulations for the assessment method of bearing capacity in in-service bridges has also been formulated in China, and Some scholars have done further research [8–10]. Due to the undercutting of the river bed, the bridge foundations are too shallow to collapse and damage it. Experts and scholars at home and abroad pay more and more attention to the influential factors and reinforcement measures of bridge diseases caused by riverbed undercutting. Taking a bridge in Hubei as an example, Zhou Shun et al. [11] analyzed the diseases and reinforcement technology of pile-column pier with undercutting of river bed and studied the factors affecting the buckling and instability of pile foundation. Li Qingwen [12] studied the influence of riverbed undercutting on the buckling mode, stability and displacement of pier top. At present, the domestic research on the influence of riverbed undercutting on the safety and stability of bridge foundation caused by sand mining and other factors is not enough, especially the research on the reinforcement method of riverbed undercutting and the influence of bridge mechanical properties before reinforcement. In this paper, taking a reinforced concrete half through arch bridge and rigid frame arch bridges as examples, the appearance inspection and disease analysis of piers and pile foundations are carried out. The structural model is established by ANSYS.
According to the modified theoretical calculation model, the structure of a bridge is analyzed. The results of bridge actual disease is compared with the theoretical calculation results to analyse the cause of the disease, and the corresponding reinforcement technology is summarized.

2. Project Background
The bridge-span combination is 2×45m+2×80m+16×45m, with a total length of 1083.26m. The upper structure of the main bridge is a reinforced concrete half-bearing arch with a clear span of 80m, and the distance between piers and piers is 86m. The approach bridges are a rigid frame arch with a clear span of 45m and a reinforced concrete T-beam channel with a span of 16m. Open caisson foundation is used for the pier at the junction of main span and approach bridge, and the rest piers are bored pile foundation. composite abutment is adopted it. The geology of the substructure of the bridge is fine sand, clayey soil, medium sand, coarse sand, pebble, strongly weathered granite, moderately weathered granite etc in sequence. The pier2# and pier4# are caisson foundation. The base is embedded at pebble layer, and the design depth of embedded foundation buried is 8.5m and 16m respectively. It is shown in figure 1.

![Figure 1. Elevation of bridge.](image1)

![Figure 2. The cracks of the pier.](image2)

3. Foundation Disease and Causal Analysis

3.1. Foundation Disease
After testing, the main diseases are as follows:
   a) The erosion of foundation section is serious, as shown in table 1.
   b) There are vertical cracks from top to bottom on the pier, and there are many longitudinal cracks in the longitudinal bridge direction and short oblique cracks on the top of the pier. Most of the cracks are much wider than the standard limit. The width of the cracks is large, which greatly exceeds the the
standard limit. The pile cap was on the river bank, but now the pile foundation is exposed due to scouring. The bottom surface of the pile cap is honeycomb. It is shown in figure 2.

c) The diameter of the pile is reduced at the junction of the lower end of the concrete casing and the backfill. The surface of the pile is uneven and the concrete falls off. The exposed reinforcement was found within 1.4m away from the riverbed in the 3rd pile of pier7# in the approach bridges. One stirrup was exposed with a length of 0.2m and about one fifth of the reinforcement was exposed in the 4th pile of pier7# in the approach bridges.

| Number | Design flow (m³/s) | Design water level of original section (m) | Minimum scouring line elevation of original section (m) | Design water level of current section (m) | Current minimum scouring line elevation (m) | Design water level reduction (m) | Erosion line reduction (m) |
|--------|-------------------|------------------------------------------|------------------------------------------------------|------------------------------------------|------------------------------------------|-------------------------------|--------------------------|
| 1      | 7201.71           | 9.63                                     | -6.69                                                | -9.03                                    | 2.34                                     | 2.78                          |                          |
| 2      | -7.25             |                                          | -6.61                                                | -10.03                                   | 2.78                                     | 1.44                          |                          |
| 3      | -6.61             |                                          | -9.06                                                | -8.05                                    | 1.44                                     | 0.95                          |                          |
| 4      | 7201.71           | 9.63                                     | 4.96                                                 | 4.67                                     | 0.95                                     | 0.87                          | 2.3                      |
| 5      | -7.52             |                                          | -9.06                                                | -8.39                                    | 2.78                                     | 2.58                          |                          |
| 6      | -5.44             |                                          | -8.02                                                | -8.03                                    | 2.78                                     | 3.63                          |                          |
| 7      | -4.4              |                                          | -8.02                                                | -8.03                                    | 3.63                                     | 2.3                           |                          |
| 8      | -5.73             |                                          | -8.03                                                | -8.03                                    | 2.3                                      |                               |                          |

3.2. Cause Analysis of Foundation Diseases

The pier2# and pier4# piers are caisson foundation, and the base is embedded in pebble layer. However, due to excessive sand mining, the buried depth of the two piers is 4.8 m and 8 m respectively before the bed surface is cut down seriously. Although the bearing capacity can meet the requirements, the anti thrust stiffness is obviously weakened and can not resist the horizontal thrust. Except for the pier5# which is embedded in the strongly weathered granite, the rest of the pile foundations are embedded in the pebble layer. Due to the serious undercutting of river bed, the free length of pile foundation increases, the anti push stiffness decreases, and the lateral displacement increases. Because of these reasons, the original arch bridge design boundary conditions change. The pier foundation and the main structure on the arch can not meet the structural requirements, resulting in various structural diseases.

The main reason for the vertical cracks is the uneven settlement at the abutment. Because of the change of boundary conditions, the vertical and oblique cracks appear in the pier body and top, resulting in large transmission force in the upper structure and less transverse reinforcement in the pier body. shear cracks are formed on the lower part under the influence of temperature and shrinkage.

4. Calculation of Pier, Pile Foundation and Open Caisson Foundation

4.1. Calculation of Pier2# and Pier4#

4.1.1. Establishment of Finite Element Model. Based on the original design documents and the actual site investigation, considering 7m scouring depth of open caisson foundation, the model is established by ANSYS, as shown in figure 3. The model is established by three-dimensional solid model. The caisson and pier are made of C20 concrete, and the pier cap is made of C30 concrete. The bottom of
open caisson is consolidated. The lateral action of soil is simulated by soil spring on the side wall of open caisson. In order to consider the buried depth of open caisson after scouring, the simulation depth is 8m.

**Figure 3.** 3D-model for bridge.

**Figure 4.** Stress of pier2# and pier4# in Y direction (vertical bridge direction).

4.1.2. Main Stress Distribution of Pier2# And Pier4#. The main tensile stress is mainly distributed near the bottom of the pier and the top of the pier cap at the mid-supported arch, showing that the main tensile stress characteristics on the top and bottom is large and the middle part of the pier body is small. The maximum main tensile stress is 4.6MPa at the corners of the pier bottom. The cracks may expand to the pier body through the pier cap, which is in good agreement with the actual crack morphology. The main tensile stress of rigid frame arch is mainly distributed in the parts of two upper corners of pier body near the half through arch rib. The maximum main tensile stress is 1.3Mpa, which is in good agreement with the actual distribution of cracks. It is shown in figure 4.

4.2. Pile Foundation Calculation
The pile foundations of pier5# and pier6# of rigid frame arch are friction piles. The depth of pile foundation scouring in the design is calculated as 7m, and the whole bridge is full of steam-20 load. The internal force combination of the bottom of pier5# and pier6# is shown in table 2.

| Number | Internal force combination | Nmax (kN) | V (kN) | M (kN•m) | Number | Internal force combination | Nmax (kN) | V (kN) | M (kN•m) |
|--------|---------------------------|-----------|--------|----------|--------|---------------------------|-----------|--------|----------|
| 5#     | Limit combination 1(all)  | -31448    | 22     | 1554     | 6#     | Limit combination 1(all)  | -30950    | -41    | -381     |
|        | Limit combination 2(all)  | -29360    | -215   | 3120     |        | Limit combination 2(all)  | -28862    | -60    | -199     |
|        | Limit combination 3(all)  | -29874    | 163    | 848      |        | Limit combination 3(all)  | -29372    | -177   | -274     |

Table 2. Internal force combination at the pier cap bottom of pier5# and pier6# with full load.
According to the calculation results, the maximum force value of pile top is 3997kN. The bearing capacity of pile foundation is slightly less than 4070kN which is original designal pile top force and less than the requirement of foundation bearing capacity. Pile foundation reinforcement only needs to be for detailing reinforcement. This force only considers the one-way bending moment and not the transverse bridge bending moment, so the calculation result is too small.

The pile top force is calculated by the modified theoretical model, shown in table 3. The maximum force of pier5# piles top is 5052kN, and that of pier6# piles top is 5149kN. which is larger than the pile foundation bearing capacity calculated in the current scouring situation. The bearing capacity of pier5# is 4976kN, and that of pier6# is 4567kN. Because of the lateral bending moment caused by the lateral eccentric load of live load in spatial model, the distribution of piles top force is uneven. When the maximum value of pile top force appears, the minimum value of pier5# distal pile top force is 4400kN, and that of pier6# distal pile top force is 4586kN. Therefore, based on the modified theoretical model, the pile top force can not meet the foundation bearing capacity requirement in the current scouring situation. It is suggested to add piles for pier5# to pier7# piles with serious impact brush and throw rubble to prevent erosion expansion.

**Table 3.** The maximum value of top force for pier5# and pier6# .(kN)

| the Maximum value of top force for pile | 5-1#  | 5-2#  | 5-3#  | 5-4#  | 5-5#  | 5-6#  | 5-7#  | 5-8#  |
|----------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| for pier5#                             | -4400.5 | -4584.4 | -4535.7 | -4709.8 | -4660.0 | -4844.4 | -4850.8 | -5052.8 |
| the Maximum value of top force for pile | 6-1#  | 6-2#  | 6-3#  | 6-4#  | 6-5#  | 6-6#  | 6-7#  | 6-8#  |
| for pier6#                             | -4586.8 | -4640.4 | -4739.2 | -4734.4 | -4887.6 | -4848.0 | -5064.9 | -5149.9 |

5. Foundation Maintenance and Reinforcement Design

5.1. **Reinforcement of Pier Cap and Body of Pier2# and Pier4#**

The reinforcement of pier cap of Pier2# and Pier4# in figure 1 adopts is strengthened by enlarging section and applying a certain amount of prestress to make the structure in an active stress state, reduce the probability of cracks appearance and enhance the durability of the structure. For the vertical and oblique cracks of Pier2# and Pier4#, the cracks should be closed first, and then the pier body should be reinforced with reinforced concrete by enlargement section method. It is shown in figure 5.

5.2. **Substructure Reinforcement**

According to the test, the method of adding piles to increase the anti-pushing rigidity is adopted for pier3#, pier5# and pier7# pile foundation, and the gabions method is adopted for the riverbed to protect the open caisson and pile foundation under the water to prevent the further expansion of scouring.
6. Conclusions
In this study, the modified theoretical calculation model is analysed. Compared with the results of a bridge actual disease and the theoretical calculation results, the cause of the disease and the corresponding reinforcement technology are summarized. Based on the analytical results, the conclusions are drawn as follows:

1) The increasing of scouring depth leads to the change of the original arch bridge design boundary conditions, the reduction of the pier foundation anti thrust pier rigidity. The main structure on the arch is no longer able to meet the structural stress requirements, resulting in the occurrence of various structural diseases.

2) According to the modified theoretical calculation model, the actual diseases of the foundation including cracks distribution area and erosion situation are in good agreement with the theoretical calculation results.

3) The pier cap adopts enlarging the section and applying a certain amount of prestress to reduce the probability of cracks appearance. The cracks of pier body are closed and then reinforced with reinforced concrete. It adopts the method of adding piles to increase the anti push rigidity in the pile foundation.

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