Study on Nondestructive Testing and Evaluation Technology for Service Performance of Existing Bridge Pile

Dong Ren¹, Conghua Huang¹, Xing Song¹, Hao Chen¹, Yuanpeng Peng¹, Jun Yang²,³*, Xiao Li Sun²,³

¹Public Works Bureau of Guangming District, Shenzhen 518106, China
²Guangzhou Municipal Engineering Testing Co., Ltd., Guangzhou 510520, China
³Guangdong Provincial Research Center for Testing and Monitoring Technology of Prefabricated Underground Structure, Guangzhou 510520, China
Email: 175805466@qq.com

Abstract. For existing bridge piles where the superstructure has been built, traditional pile test methods are difficult to apply. In this paper, a nondestructive testing and evaluation technology for service performance of existing pile is put forward. Based on a reinforcement case of existing municipal bridge, the nondestructive method (parallel seismic wave method) is applied to detect pile defects and bearing capacities. In the field test, two excitation types are compared to acquire better stress wave signal quality. The result shows that the length and structural defects of piles can be detected by the parallel seismic wave method. The vertical excitation at bridge superstructure is more conducive to strengthen the first arrival wave characteristics. And the bearing capacity of existing piles can be further estimated based on the soil stratum conditions revealed by the test boreholes and the given survey parameters.

Keywords: Existing bridge pile, Nondestructive testing, Performance evaluation, Parallel seismic wave method

1. Introduction

In the field of the traffic engineering, many existing bridges in China were built in the early stage, with low design standards, poor construction and lack of quality testing. Many pile foundations have not undergone strict quality testing after completion. Due to historical reasons, the original design and construction drawings of the pile are mostly incomplete or lost. After careful investigation and verification, the superstructure of bridge can rebuild or supply the technical data. However, a considerable part of pile foundations cannot be inspected or tested. So technical files cannot be established, and the quality of piles remains in an unknown state for a long time.

Traditional low-strain reflected wave method, ultrasonic wave method and core drilling method have been widely used in pile integrity testing of construction projects, and the theoretical results of these methods are relatively rich. However, for the existing bridge piles where the superstructure has been built, the methods above are difficult to be directly applied. Some researchers have carried out theoretical and experimental studies on the testing methods of existing pile service conditions. Kenai et al. [1] tested and analyzed 11 pile foundations in an airport reconstruction project. In addition to testing the pile depth, they tried to judge the pile quality by processing the average P-wave velocity. Sack et al. [2] used dynamic penetration equipment to carry out the parallel seismic (PS) method of soil characteristics and pile length. Wu et al. [3] used the PS method to detect the integrity of a pile with abnormal results in static loading test. Lo et al. [4] introduced the instrument system and testing
procedure of PS test, and applied this method to successfully detect the depth of a bridge pier foundation. Wu et al. [5] combined the magnetic method and the PS method to detect pile and steel cage length, and compared the test accuracy of the two methods. Huang et al. [6] compared the test results of the PS wave method before and after adding the cap on the precast pipe pile top, and found that the pile depth can be determined for the pile connected with the cap. However, the existing achievements mainly focus on the non-destructive testing method for pile length detection, and there is no detailed case reports on the performance evaluation of the existing bridge piles.

Based on the requirement of the disease investigation and structure reinforcement of an existing municipal bridge in Guangzhou, the paper intends to carry out the following works: (1) investigation of unfavorable geological conditions in bridge site and analysis of deformation monitoring data; (2) formulation and implementation of nondestructive testing scheme for bridge pile foundations; (3) pile defects detection analysis and bearing capacity calculation. Through the comprehensive testing and evaluation of the service performance of the bridge pile foundations of the project, it can provide references for the detection and reinforcement engineering of the similar existing bridge foundation in the future.

2. Project Overview
The municipal bridge (also known as old bridge) in Guangzhou was completed in 1989, with a total length of 256 m, and across the Guangzhou North-Ring Highway. The main bridge adopts reinforced concrete constant height continuous T beams, and the substructure are three-pillar piers and pile foundations, as shown in figure 1.

(a) Surrounding environment of bridge site.

(b) Satellite map of bridge site.

Figure 1. The current situation of old bridge.
Since the bride pile foundations are located in the soft soil layer, the settlement of the bridge has continued since its completion. Table 1 summarizes the accumulated settlements of piers (No.1 ~ No.6) during the period from the completion of the bridge to the construction of the excavation of the subway station. It can be seen that before the excavation, the accumulated settlements of No.1, No.2 and No.5 piers is relatively larger, and the settlement of No.2 pier is 162.8mm, which is quite obvious compared with No.1 and No.3 piers.

Table 1. Monitoring settlements of pier (No.1 ~ No.5) before excavation construction (unit: mm).

| Pier No. | No.1 | No.2 | No.3 | No.4 | No.5 | No.6 |
|----------|------|------|------|------|------|------|
| Historical settlement | 69.2 | 162.8 | 13.4 | 41.4 | 79.1 | 35.4 |

Figure 2 shows the settlement curves of pile foundations of bridge pier No.1 ~ No.5 in excavation construction stage. It can be seen that from April 2014 to June 2016 (before excavation), the maximum settlement of the No.2 bridge pier was 20.3 mm. When the foundation pit was excavated to the depth of 9.5 m, the additional settlement of Pier No.2 was 13.9 mm. To July 2019, the accumulated settlement of No.2 bridge pier had exceeded 200 mm.

In view of the low early design load and poor service performance of the bridge, a new bridge widening project and the subway station excavation are implemented next to the old bridge. As shown in figure 3, the old bridge has suffered severe structural damage after servicing for many years. There are a large number of diagonal and vertical cracks on the webs of the bridge girder. Some cracks extend to the bottom plate and penetrated both sides of the web. The maximum crack width is more than 0.4 mm. In order to ensure the safety of bridge, steel plates are pasted on the bottom of the beam for reinforcement, and steel frame diaphragms are erected between the beams to strengthen the overall connection between the main beams.
In order to correctly evaluate the current service performance and provide the references for the reinforcement design of the old bridge, the authors applied the parallel seismic (PS) method to detect the pile length and the integrity of the three pile foundations of No.2 bridge pier, and evaluated the bearing capacity of pile foundations based on the geological surveys, pile foundation design and construction data.

3. Field Testing
Figure 4 shows the pile foundation design drawing of No.2 bridge pier. According to the design data, the pile diameter of No.2 pier is 1 m, the length of pile is 23 m, the pile tip passes through the silt soil layer and enters into the gravel layer. The bearing type is friction end bearing pile.
Considering the clearance under the bridge is limited, a small geological drilling rig is used to carry out geological drilling near No.2 bridge pier, and the survey borehole is used as the testing hole of PS method. The location relationship between the testing holes and the piers is shown in figure 5. Due to the shielding of temporary steel supports near the bridge pier, the minimum distance between the testing hole and the testing pile is about 1.6 m. As the pile cap is buried below the ground, the field test applies two excitation types, transverse knocking at the side of the pier and longitudinal knocking at the bottom of the top beam, are used in the field as shown in figure 6.
Table 2 shows the relevant information of testing boreholes in PS test.

| Testing hole | Testing pile | Borehole depth (m) | Pile to borehole distance (m) |
|--------------|--------------|--------------------|------------------------------|
| CK1          | P2-1         | 35.5               | 1.7                          |
| CK2          | P2-2         | 34.5               | 1.6                          |
| CK3          | P2-3         | 34.5               | 1.7                          |

4. Analysis of the Results

4.1. Site Geological Condition

The depth of groundwater level in the site is 0.3~3.5 m. According to the geological conditions revealed by drilling in situ, the main types include miscellaneous fill, silt, silty clay and coarse-gravel sand (from top to bottom). The depth below 30 m is strong to slightly weathered limestone, and karst caves are generally developed. Figure 7 is the photo of core sample (depth: 36 m) obtained by drilling on the site.

Figure 7. Photo of core sample from ZK-1 drilling core.

Figure 8 is the geological section of the site where No.2 bridge pier is located based on the drilling results of the project and the investigation data of surrounding excavation. Comprehensive analysis shows that the rock and soil layers of the site where the old bridge is located fluctuates greatly, the thickness of silty soil layer and silty clay layer are larger, and there are strong permeable soil layers such as gravel, coarse sand and silty sand, and the rock formation is limestone. The south end of the old bridge (pier No.0 to No.4) has large rock surface undulations. There are grooves under the pile tip of No.2 pier, which may have relatively developed karst caves that unfavorable to the bridge and ground settlements induced by excavation and dewatering.
4.2. Pile Length and Integrity

After the soil around the borehole is stabilized for one week, the PS method is used to detect the length and integrity of the bridge pile. Figure 9 shows the time-depth curves of P2-1 and P2-2 obtained by PS test. The apparent speed of pile foundations under No.2 pier is about 3600 m/s, and the concrete quality of piles is intact. The initial arrival time of the stress wave near the surface is longer, which is due to the larger permeability and the higher unsaturated degree of the shallow soil layer. Although the velocity and amplitude of the stress wave at the depth of 10.5 m–18 m are significantly reduced, the apparent wave velocity of the lower part is consistent with the upper part and there is no first arrival wave delay. Considering the distribution of the soil layer, the decrease of the wave velocity is caused by the soft silt. Due to the larger pile-borehole distance the speculated pile length is corrected using the translation method. The inflection point of stress wave fitting line can be seen clearly at the depth of 25 m, which is judged as the position of pile tip, indicating that the construction pile length meets
the design requirements. Based on the soil layer revealed by drilling, the side and bottom of the testing pile are both soft soil layers, which is inconsistent with the design of end bearing pile. The bearing stratum of piles on both sides of No.2 bridge pier (P2-1, P2-3) are coarse sand and gravel sand. The bearing stratum of the intermediate pile (P2-2) is saturated soft plastic - flow plastic silty clay with SPT N-value of 1~3.

Figure 9. Test results of PS method (longitudinal knocking at the bottom of top beam).

Figure 10 shows the time-depth curves of stress wave of bridge piles obtained by transverse excitation. Compared with curves in figure 9, the energy of P-wave transmitted downward during horizontal knocking is not as large as that of S-wave, resulting in the amplitude of first arrival P-wave received by hydrophone is smaller than that of S-wave arrived later. Therefore, it is more difficult to distinguish the pile length and integrity by the first arrival waves. The first arrival time and amplitude of the first wave are clearer when longitudinal knocking is adopted, which is closely related to the P-wave component mainly generated by longitudinal knocking.
Figure 10. Test results of PS method (transverse knocking at the side of pier)

4.3. Bearing Capacity of Bridge Pile

According to the field test results of bridge piles and the code for design of pile foundation (JTG 3363-2019) [7], the bearing capacity of existing piles under No.2 bridge pier is evaluated by comprehensive utilization of bridge widening engineering survey data, bridge pile foundation design and construction data and geological drilling data. Table 3 shows the physical and mechanical parameters of soil layer in the calculation of pile bearing capacity.

Table 3. Recommended calculation parameter values for pile bearing capacity.

| Index | Stratum                           | Ultimate side friction (kPa) | Allowable bearing capacity (MPa) | Compressive strength of rock (MPa) | Coefficient of friction at pile end | Coefficient of total resistance of end bearing strata C₁ | Coefficient of total resistance of pile side rock C₂ |
|-------|-----------------------------------|-----------------------------|---------------------------------|-----------------------------------|------------------------------------|------------------------------------------------------|--------------------------------------------------|
|       | Filling soil                      | Unfinished self-weight consolidation |                                |                                   |                                    |                                                      |                                                  |
| Silt  | 15                                | 60                          |                                 |                                   |                                    |                                                      |                                                  |
| Silt clay | 15                              | 80                          |                                 |                                   |                                    |                                                      |                                                  |
| Silty clay | 60                              | 180                         |                                 |                                   |                                    |                                                      |                                                  |
| Fine sand | 60                              | 130                         |                                 |                                   | 0.35                               |                                                      |                                                  |
| Coarse sand | 180                             |                             |                                 |                                   |                                    |                                                      |                                                  |
| Gravelly sand | 80                              | 280                         |                                 |                                   | 0.35                               |                                                      |                                                  |
| Strong weathered limestone | 160                             | 450                         |                                 |                                   | 0.45                               |                                                      |                                                  |
| Medium weathered limestone | —                               | 3000                        | 20                              |                                   | 0.60                               | 0.4                                                  | 0.03                                            |
| Micro-weathed limestone | —                               | 4500                        | 65                              |                                   | 0.70                               | 0.5                                                  | 0.04                                            |

Table 4 shows the calculated bearing capacity of three bridge piles. It can be seen that the calculated bearing capacity of pile P2-1 and P2-3 is greater than the original design bearing capacity. Affected by unfavorable factors of site strata, the calculated bearing capacity of pile P2-2 is reduced by 26% compared to the design value, which can not meet the design requirements.
### Table 4. Comparison of calculation results of pile foundation bearing capacity

| Bridge pile | Location       | Design bearing capacity (kN) | Calculated bearing capacity (kN) | Percentage of reduction |
|-------------|----------------|------------------------------|----------------------------------|------------------------|
| P2-1        | west side      | 1972                         | 2168                             | —                      |
| P2-2        | middle         | 1972                         | 1458                             | 26%                    |
| P2-3        | east side      | 1972                         | 2340                             | —                      |

### 5. Conclusion

1. By analyzing the fitting line distribution of first arrival stress wave in the PS method, the structural defects of the pile can be identified. Combined with the stratum conditions revealed by the test boreholes and the given survey parameters, the actual bearing capacity of the bridge pile foundation can be further estimated.

2. Because the water coupling mode in the borehole has filtering effect on shear wave, the upper structure excitation should produce longitudinal wave as far as possible. The vertical excitation at the bottom of top beam is more conducive to strengthen the first arrival wave characteristics than the transverse excitation at the side of pier, so as to reduce the difficulty of signal analysis in the PS method.

3. Through the engineering case study in this paper, it can be seen that the PS method has obvious advantages in the detection of old bridge pile foundation service performance, which can solve the problem of existing pile foundation evaluation, and provide an important reference for similar existing foundation detection in the future.

### Acknowledgement

This project was supported by Science and Technology Planning Project of Guangzhou Municipal Construction Group Co., Ltd ([2019]-KJ014; [2020]-KJ019).

### References

[1] Kenai S, Baha R R 2003 Evaluation and repair of Algiers new airport building [J] Cement and Concrete Composites 25(6): 633-641.

[2] Sack D A, Slaughter S H, Olson L D 2004 Combined measurement of unknown foundation depths and soil properties with nondestructive evaluation methods [J] Transportation Research Record 1868(1): 76-80.

[3] Wu B J, Ji M X, Yang H, et al. 2012 Research on nondestructive detection technology of reinforcement cage length and long pile length in cast-in-situ pile [J] Chinese Journal of Engineering Geophysics 9(3): 371-374. (in Chinese)

[4] Lo K F, Ni S H, Charng J J, et al. 2008 Time-frequency signal analysis for nondestructive evaluation of pile with cap Advanced Materials Research 47: 9-12.

[5] Wu B J, Yang H 2009 Using parallel seismic and magnetic to detect length of prestressed concrete long tube pile [J] Quality of Civil Engineering and Construction 27(1): 27-29. (in Chinese)

[6] Huang Y H, Ni S H 2012 Experimental study for the evaluation of stress wave approaches on a group pile foundation [J] NDT & E International 47: 134-143.

[7] JTG 3363-2019 Specifications for Design of Foundation of Highway Bridges and Culverts [S] 2007. (in Chinese)