Study on Interaction of RC Pile-Soil with High Reinforcement Ratio of Integral Abutment Bridges under Quasi-Static Test

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Abstract. In order to improve the ability of the reinforcement concrete (RC) pile foundation of integral abutment to absorb the horizontal reciprocating deformation under the action of temperature or earthquake, a pseudo-static low cycle test on interaction of pile-soil with high reinforcement ratio was carried out. The failure location, hysteresis curve, skeleton curve and horizontal deformation of three piles with different reinforcement ratios were compared. The test results show that, with the increase of the reinforcement ratio, the crack of the RC pile develops along the pile body to the depth, and the pile body failure area and the position where the maximum bending moment moves down, the crack resistance of the pile body is improved, and the effective interaction pile length increases; The test results also show that the hysteresis curve of the model pile becomes fuller with the increase of the reinforcement ratio, compared with the RCP-1 specimen with the lowest reinforcement ratio, the equivalent viscous damping ratio of the RCP-3 specimen is increased by 31.6%, and the energy dissipation capacity is improved. In addition, with the increase of the reinforcement ratio, the bearing capacity and deformation capacity of model piles are greatly improved. Compared with RCP-1 specimen, the ultimate bearing capacity of RCP-3 specimen increased by 150%, and the corresponding ultimate displacement increased by 153%. Increasing reinforcement ratio can significantly improve the mechanical properties and deformation capacity of RC pile.

1. Introduction
The integral bridge eliminates the expansion joints and expansion devices, and connects the superstructure, abutment and pile foundation as a whole, which has good seismic performance and life cycle, reduces the operation and maintenance costs, and has been widely popularized and applied in Europe, America and Japan[1-6]. China has gradually started to apply it. The latest standard for design of concrete structures durability [7] (GB/T 50476-2019) has clearly required that small and medium-span bridges should give priority to integral bridges. However, the reciprocating displacement of the main girder of the integral bridge under the action of ambient temperature or earthquake will drive the horizontal reciprocating motion of the abutment, which will lead to a large horizontal deformation of the pile foundation at the bottom of the abutment, and then cause the pile-soil interaction. Therefore, the integral bridge pile foundation has higher requirements for resisting horizontal deformation. The greater
the temperature difference and bridge length, the greater the horizontal deformation, and the higher the
requirement for the deformation ability of pile foundation.

In order to meet the needs of high horizontal deformation resistance, H-shaped steel pile foundation is mostly used for pile foundation at the bottom of integral abutment built abroad [8-11]. However, due to economy, engineering experience and habit, the common pile foundation for bridges in China is concrete pile (RC). RC piles are also used in the pile foundation of integral bridge in China. The research shows that [12-15], the horizontal deformation resistance of the traditional RC pile foundation reinforced only by the structure is low, so it is difficult to apply to the integral bridge, which limits the popularization of this type of bridge.

In order to improve the deformation resistance of RC pile foundation, scholars of domestic and foreign have carried out extensive research. Literature [16] improves the flexibility and deformation ability of pile body by reducing the diameter of section in a certain range at the top of pile, and studies the interaction between stepped pile and soil; However, due to the earth pressure around the pile, reducing the cross-section size can only improve its flexibility, but has little effect on improving its deformability. Literature [17] reduces the earth pressure around the pile and increases the horizontal deformation ability of the pile by reaming the pile top within a certain depth range and filling loose sand in the reaming, which is applied to the longest integral bridge in China-Yong-chun Shang-ban Bridge; However, due to the horizontal reciprocating interaction between pile and soil, loose sand will be gradually compacted, and the use effect will gradually decrease. Literature [18] has carried out the research of reaming depth and reaming material, and increased its horizontal deformation ability by reaming and filling rubber in a certain depth range of pile top: In addition, reference [19] improves the horizontal deformation ability of RC pile foundation by wrapping the pile body. These methods can improve the horizontal deformation ability of RC pile foundation, but the construction is inconvenient.

In addition, the pile-soil interaction test of PHC pipe pile in Reference [20] showed that the higher the reinforcement ratio and prestress degree were, the better the deformation performance was. Literature [21] has carried out numerical analysis on the parameters of concrete pile of integral bridge, and the influence of strong axis and weak axis of concrete pile on the mechanical performance of integral bridge is studied. It is considered that the horizontal deformation capacity of integral bridge can be improved by taking weak axis as the stress direction. Literature [22] thinks through finite element simulation that increasing the height of abutment can reduce the horizontal displacement of the top of pile foundation, but experimental research and in-depth finite element analysis have not been carried out.

Because the traditional concrete pile foundation has low reinforcement ratio and low horizontal deformation resistance, it is not suitable for the pile foundation of integral bridge. However, according to the above research summary, there are few researches on the anti-deformation ability of RC piles and pile-soil interaction of integral bridges with high reinforcement. Therefore, this paper has carried out the reciprocating low-cycle pseudo-static test of RC pile-soil interaction with high reinforcement to study the influence of reinforcement ratio on its horizontal deformation resistance, which provides reference for the popularization and application of this type of bridge in China.

2. Brief Introduction of Test

2.1. Model Pile Design

According to the different reinforcement ratio, one RC pile specimen with lower reinforcement ratio (0.8%) and two RC pile specimens with higher reinforcement ratio (1.6% and 3.2%, respectively) were designed and manufactured. The numbers of the three piles are RCP-1, RCP-2 and RCP-3 respectively. The pile length and diameter of each specimen are 3.5m and 155mm respectively.

The specimen is C40 concrete. The measured 28-day strength of concrete cube test block is 47.6MPa, and the elastic modulus is 3.25x104MPa. Longitudinal reinforcement adopts HRB335, and steel bars with diameters of 6mm, 8mm and 12mm are adopted according to different reinforcement ratios. The stirrup adopts HPB235, circular stirrup with diameter of 6mm, and the stirrup spacing in non-encrypted
area is 120mm; The 600mm range of pile top and bottom is stirrup encryption area, and the encryption
distance is 100mm; Thickness of protective layer is 20mm. Figure 1 only shows the reinforcement
schematic of RCP-1 model pile, and other components are arranged similarly, so they are not given one
by one due to the limitation of space.

2.2. Soil Box and Soil Parameters
The rectangular steel box with length of 3m, width of 2m and height of 4m is selected as the soil box,
as shown in figure 2. The bottom of the soil box is welded with 4 angle steels with a length of 0.2m to
fix the bottom of the pile.

The relevant parameters of the test sand are shown in table 1, according to code for investigation of
geotechnical engineering (GB50021-2001), the test sand belongs to medium coarse sand. Before the test,
the model pile is placed in the soil box, and then the sand is filled in the soil box and vibrating
densification. After sand filling, the depth of the model pile is 3.1m, and the exposed part above the sand
surface is 0.4m.

| Types of soil      | Moisture content ω [%] | Density ρ [g/cm³] | Void ratio e | Angle of internal friction ϕ [°] | Modulus of compression [Mpa] | Average standard penetration number | Relative compaction |
|-------------------|------------------------|-------------------|--------------|---------------------------------|----------------------------|-----------------------------------|-------------------|
| Medium coarse sand | 0.8                    | 1.50              | 0.80         | 35.86                           | 28.9                       | 11                                | 53%               |

![Figure 1. Reinforcement arrangement of RCP-1 specimen.](image1)

![Figure 2. Soil-box.](image2)

2.3. Measuring Point Arrangement
Each side of the pile is arranged 10 strain gauges, symmetrically arranged on both sides, a total of 20.
Strain gauge measuring points are arranged down at a distance of 350mm from the pile-soil junction,
numbered from S1 to S20, as shown in figure 3a.

Eight pairs of soil pressure gauges (8 on each side, 16 in total) are symmetrically arranged along the
stress direction of the pile. The layout method starts from 175mm down at the pile-soil junction and is
arranged at a distance of 350mm, numbered from T1~T16, as shown in figure 3b.

In addition, 13 horizontal displacement meters (L1~L13) were arranged in this experiment. Among
them, L1 is located at the top of the pile, which is used to compare the stroke of MTS actuator; other
displacement meters are arranged at 200mm intervals from the pile-soil junction and become 600mm at
the bottom, as shown in figure 3c.
2.4. Loading Method

In this experiment, MTS electro-hydraulic servo loading system of Fuzhou University is used to apply reciprocating horizontal displacement to the top of model pile. The specific loading scheme is as follows: 1. Apply reciprocating displacement to the top of pile by 2mm, 5mm, 8mm and 10mm in the initial stage of loading; 2. When it is 10mm~30mm, it will increase according to the displacement increment of 5mm, that is, the loading displacement is 10mm, 15mm, 20mm, 25mm and 30 mm in turn; 3. When the displacement exceeds 30mm, make the displacement increment of each stage be 10mm, until the corresponding horizontal load is equal to or less than 0.85 of the maximum bearing capacity under a certain amplitude displacement, the experiment is stopped. In the experiment, the loading speed is 1.0mm/s, each load cycle is three times, and the load is held for 1 minute before the loading direction is changed. The loading history is shown in figure 4.

3. Test Result Analysis

3.1. Pile Failure Characteristics

After the experiment, the failure of model pile was observed, and it was found that the failure area of RCP-1 model pile was 2.8D~4.5D. The first slight crack appeared at 2.8D (D is the pile diameter). At 3.5D, the pile concrete was severely crushed and damaged, the steel bars were exposed, and some steel bars were broken. At 4.5D, there is obvious cracking of pile concrete, as shown in figure 5. The location and failure mode of RCP-2 model pile are similar to those of RCP-1 model pile, and the failure area is
2.9D to 4.6D. However, the failure area of RCP-3 model pile is 4.8D–6.8D, and there are four obvious cracks in the pile body.

### Figure 5. Damages and failure of RCP-1.

It can be seen from the comparison of each specimen that the crack position of RCP-3 is obviously lower than that of RCP-1 and RCP-2, and a crack appears at a deeper position, which indicates that with the further increase of reinforcement ratio, the depth of the failure position of RCP-3 pile body increases, the effective interaction length increases, and materials are effectively utilized. It shows that the larger reinforcement ratio has a great influence on the failure mode of RC piles.

### 3.2. Hysteresis Curve and Equivalent Viscous Damping Coefficient

The area enclosed by the hysteresis loop can be used to measure the energy dissipation capacity of pile-soil system in earthquake resistance. Figure 6 shows the hysteresis curve of RCP-1 model pile. It can be seen from Figure 6 that the hysteretic curve of the model pile is centrosymmetric as a whole, which shows that the mechanical properties of the model pile under forward and reverse loading are similar. At the initial stage of loading, the force-displacement curve of model pile is linear, the area of hysteresis loop is small, and the model pile is in elastic state. With the increase of displacement load, the area of hysteresis loop increases, the energy dissipation capacity of pile-soil system increases, and the pile-soil interaction becomes more obvious.

Figure 7 shows hysteretic curves of three model piles under 50mm displacement load. It can be seen from the figure that under the same displacement load, the horizontal force of RCP-1 is the smallest, which is 7.2kN; the horizontal forces of RCP-2 and RCP-3 are 9.9kN and 13.2kN respectively, which are increased by 37.5% and 83.3% respectively compared with RCP-1. With the increase of reinforcement ratio, the hysteretic curve of model pile becomes fuller and the area surrounded by hysteretic loop becomes larger, which indicates that increasing reinforcement ratio of model pile can enhance the anti-push ability and pile-soil interaction ability of model pile.
The equivalent viscous damping ratio $\xi_e$ can be used to measure the energy dissipation capacity of the pile-soil system. Figure 8 shows a hysteresis loop, and $\xi_e$ can be calculated according to Eq. (1):

$$\xi_e = \frac{A_{ABCD}}{2\pi(A_{OFD} + A_{OBE})}.$$  \hspace{1cm} (1)

In this formula, $A_{ABCD}$ is the hysteresis loop area, $A_{OFD}$ and $A_{OBE}$ are the areas of triangle OFD and triangle OEB respectively.

Figure 9 shows the equivalent viscous damping ratio of three model piles under various loads. It can be seen from Figure 9 that the equivalent viscous damping ratio of the three model piles has the same change trend in the loading process. For RCP-1 model pile, when the displacement is less than 40mm, $\xi_e$ increases with the increase of displacement load, and reaches the maximum value when then displacement is 40mm, then decreases with the increase of displacement. This is because, in the initial stage of loading, the deformation of pile is small, which has not been fully transmitted to the lower part of pile body, and the interaction between pile and soil is not obvious, so the equivalent viscous damping ratio is small. With the increase of displacement load, the pile-soil interaction increases, the energy dissipation of pile-soil system increases, and the damping ratio also increases. However, when the displacement reaches 40mm and the concrete is crushed, the energy dissipation of the system decreases.
and the damping ratio begins to decrease. The RCP-2 and RCP-3 reached the maximum at 50mm displacement.

Figure 9 also shows that under the same displacement load, the higher the reinforcement ratio, the greater the $\xi_e$ of the model pile. Comparing the peak values of three model piles, it can be seen that the peak values of RCP-1 ~ RCP-3 are 0.19, 0.22 and 0.25 respectively. Compared with RCP-1, RCP-2 and RCP-3 increase by 15.7 % and 31.6 %, respectively, indicating that increasing the reinforcement ratio can improve the energy dissipation capacity of the pile-soil system and the seismic capacity of the model pile.

**Figure 9.** Equivalent viscous damping ratio of piles.

### 3.3. Skeleton Curve

According to the skeleton curve, the bearing capacity and deformation capacity of the pile-soil system can be evaluated. Figure 10 shows the skeleton curves of three model piles. It can be seen from Figure 10 that the skeleton curve is symmetrical in the forward and reverse directions. The skeleton curve can be divided into three parts: elastic stage, elastic-plastic stage and failure stage. It can be seen from Figure 10 that with the increase of reinforcement ratio, the deformation capacity of the model pile is significantly improved, the ultimate bearing capacity is correspondingly improved, and the corresponding displacement when reaching the ultimate bearing capacity is also significantly increased. Therefore, increasing the reinforcement ratio of model piles can improve the horizontal deformation capacity of piles, that is, RC piles with high reinforcement ratio have better horizontal deformation resistance.

**Figure 10.** Skeleton curves.

Figure 11 compares the load and displacement of three model piles under elastic limit state. The ultimate elastic loads of RCP-1-RCP-3 are 2.8kN, 4.3kN and 6.0kN respectively, and the corresponding ultimate elastic displacements are 8.0mm, 10.0mm and 15.0mm respectively. Compared with RCP-1, the ultimate elastic load of RCP-2 and RCP-3 increased by 42.3% and 110.7% respectively, and the ultimate elastic displacement increased by 25.0% and 87.5% respectively. It shows that increasing reinforcement ratio can significantly improve the deformation capacity and bearing capacity of model piles in elastic state.
Figure 11. Curves on elastic limit state.

Figure 12 shows the load and displacement of three model piles under the ultimate limit state of bearing capacity. It can be seen from figure 12 that the ultimate loads of RCP-1~RCP-3 are 7.5kN, 11.1kN and 19.0kN respectively, and their corresponding ultimate displacements are 40.0mm, 70.0mm and 100.0mm respectively. Compared with RCP-1, the peak load of RCP-2 and RCP-3 increased by 48.0% and 153.3% respectively, and the peak displacement increased by 75.0% and 150.0% respectively. It shows that increasing reinforcement ratio can significantly improve the bearing capacity and deformation capacity of model piles in ultimate state.

Figure 12. Curves on ultimate limit state.

3.4. Distribution Rule of Horizontal Deformation of Pile Along Depth Direction

Figure 13 shows the distribution law of horizontal deformation along the depth direction in the whole process of model pile test. Because the three model piles have similar horizontal deformation distribution rules under displacement load, only RCP-1 model piles are given. It can be seen from figure 13 that the distribution law of horizontal deformation of pile body gradually decreases with the increase of depth, and horizontal deformation which is obviously consistent with the loading side appears at the measuring points L1~L7 of pile body (buried depth 0.0~1.0m); And there is obvious reverse direction at the measuring point L8 of pile body (buried depth of 1.2m), as shown in figure 13. Starting from L10
measuring point (buried depth: 1.6m), the horizontal displacement of pile body is very small and basically zero.

Figure 14 is a comparison of horizontal deformation of three model piles under 20mm displacement load. It can be seen from Figure 14 that the horizontal deformation distribution laws of the three piles are basically the same. It shows that the change of reinforcement ratio of model pile has little effect on the global bending stiffness of pile-soil system. However, under the same displacement load, the deformation of RCP-1 in shallow layer soil is too large, which shows that the integrity of pile foundation with low reinforcement ratio is lower than that with high reinforcement ratio.

4. Conclusion

In this paper, the low-cycle quasi-static test of high-reinforced RC pile-soil interaction is carried out, and the following conclusions are obtained:

(1) By comparing the failure position, hysteretic curve, skeleton curve, equivalent viscous damping coefficient and deformation of three model piles, it basically shows that increasing the reinforcement ratio of RC piles can improve the pile-soil interaction effect, horizontal deformation, bearing capacity and energy dissipation capacity.

(2) The damaged area of the pile body is 2.8D~6.8D. Increasing reinforcement ratio has great influence on the failure of model pile, and the range of pile failure increases and develops along the buried depth to the deep; The effective length of pile-soil interaction increases.

(3) In the early stage of loading, the skeleton curve shows linearity; after concrete cracks, the load increases and slows down, which shows nonlinearity. Increasing the reinforcement ratio can improve the horizontal deformation capacity and bearing capacity of model piles. When the reinforcement ratio increases from 0.8% to 3.2%, the load and displacement corresponding to the elastic limit state of the model pile increase by 110.7% and 87.5% respectively; The load and displacement corresponding to the ultimate state of bearing capacity increased by 153.3% and 150% respectively.

(4) The equivalent viscous damping coefficient increases first and then decreases with the increase of displacement load. Compared with RCP-1, the maximum equivalent viscous damping ratio of RCP-3 is increased by 31.6%, its hysteretic curve is fuller, and the energy consumption of pile-soil system is stronger.

In a word, increasing the reinforcement ratio can significantly improve the mechanical performance and deformation capacity of RC pile foundation. However, only RC piles with reinforcement ratio of 0.8%, 1.6% and 3.2% are tested in this paper, and the reinforcement of RC piles can be optimized by finite element simulation and in-depth analysis. In addition, RC piles with high reinforcement can be combined with reaming at the top of piles to study their horizontal deformation ability.
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