Load-bearing Characters Analysis of Large Diameter Rock-Socketed Filling Piles Based on Self-Balanced Method

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Abstract. Self-balanced method is carried out on the large diameter rock-socketed filling piles of high-pile wharf at Inland River, to explore the distribution laws of load-displacement curve, pile internal force, pile tip friction resistance and pile side friction resistance under load force. The results showed that: the tip resistance of S1 and S2 test piles accounted for 53.4% and 53.6% of the pile bearing capacity, respectively, while the total side friction resistance accounted for 46.6% and 46.4% of the pile bearing capacity, respectively; both the pile tip friction resistance and pile side friction resistance can be fully played, and reach to the design requirements. The reasonability of large diameter rock-socketed filling design is verified through test analysis, which can provide basis for the optimization of high-pile wharf structural type, thus reducing the wharf project cost, and also providing reference for the similar large diameter rock-socketed filling piles of high-pile wharf at Inland River.

1. Introduction
In recent years, along with the large-scale construction of river ports, large diameter rock-socketed filling piles with higher carrying capacity has been generally used as the pile foundation of high-pile wharf, so how to accurately determine its carrying capacity is particularly important. Self-balanced method can accurately test the bearing capacity value of the foundation pile, which was first proposed by Japanese scholars Nakayama and Fujiseki [1]. In the 1980s, J.Osterberg [2] applied it successfully in the bridge steel piles for the first time, and formed a new type of pile foundation test technique, so it is also known as J.Osterberg test pile method, and then widely used and promoted in Europe, Singapore and other places; Li Guangxin et al [3] introduced this method into China, and carried out a large number of theoretical and model experimental researches, but no actual project site test was conducted; Followed by this, Shi Peidong et al [4] introduced the promotion and application conditions of this method in foreign countries, and discussed existing problems in domestic applications; Gong Weiming et al [5] committed to the theoretical research and engineering application of self-balancing method; the industry standard was developed after years of engineering application [5], in addition, this test technology was applied in Hong Kong-Zhuhai-Macao Bridge [6-7] and other major projects. This method has conducted a lot of researches in regards of the basic
theoretical research and practical engineering application of rock-socketed filling piles foundation, Gao Ping [8] and Zhang Mingli et al [9] studied test pile self-balanced test under the condition of soft rock; Xu Xibin et al [10] conducted comparison analysis between the actual pile test and indoor model tests of rock-socketed filling piles.

In this paper, it aims to analyze the load-displacement, tip resistance, side friction and ultimate load value based on the measured data obtained from the self-balanced method of high-pile wharf rock-socketed filling piles foundation, which can verify the reasonability of pile foundation design, and provide basis for the optimization of high-pile wharf structural type, as well as provide reference for the similar large diameter rock-socketed filling piles of high-pile wharf at Inland River.

2. Self-Balanced Method Test on Large Diameter of Rock-socketed Filling Piles

2.1. Overview of test pile

The high pile wharf piles foundation at a certain Inland River adopts reinforced concrete large diameter rock-socketed filling piles with the diameter of 2.0m or 2.3m. Two piles with the pile foundation diameter of 2cm shall be selected to have pile test, and the parameters are shown in Table 1, the engineering geological conditions are shown in Figure 1. The strength of pile concrete is 35MPa after 28 days curing, the elastic modulus is 3.5×10⁴MPa.

| No | Diameter/mm | Length/m | Top elevation/m | Bottom elevation /m | Load box bottom elevation/ m |
|----|-------------|----------|-----------------|---------------------|-----------------------------|
| S1 | 2000        | 25.7     | 179.7           | 154.0               | 155.0                       |
| S2 | 2000        | 19.7     | 179.7           | 160.0               | 160.5                       |

Through the laboratory test on the main rock-soil layer sample of S1 and S2 test pile geological drilling and sampling, the various rock layers parameters at pile test position are shown in Table 2. Combined with the practical engineering and test analysis on covering soil, the ultimate friction resistance of pile side takes 21.45kPa.

| Lithology                  | Medium-weathered mudstone | Medium-weathered sandstone |
|----------------------------|----------------------------|----------------------------|
| Compressiv strength of     | 8.03×10³                   | 25.67×10³                  |
| natural uniaxial /KPa      |                            |                            |
| Compressiv strength of     | 4.62×10³                   | 19.75×10³                  |
| saturated uniaxial /KPa    |                            |                            |
| Natural gravity /kN.m²     | 25.3                       | 24.5                       |
| Softening coefficient      | 0.58                       | 0.8                        |

2.2. Test pile load test system diagram

![Figure 1. The test system of self-balanced method](image-url)
The test system of self-balanced method is shown in Figure 1. It sets an inbuilt load box at the self-balancing point of pile, and then apply the load to load box through hydraulic device, the displacement sensor on displacement rod that lead to the ground is used to detect the deformation, the strain meter is arranged at the boundary of rock-soil layer to detect the pile strain, and the quantity of strain meter should be increased or reduced according to different rock-soil layer thickness. Thus, load-displacement (up, down, tip) curve and the stress-strain curves of strain meter under different load values can also be drawn the according to readings, so as to analyze the pile foundation bearing capacity, pile body force and pile side friction resistance distribution law along with changes of depth.

2.3. Test pile load

In accordance with the requirements of test procedures [5], slow maintain load method is adopted to conduct gradual loading, 1/15 of estimated limit value is regarded as each level load value, and the initial estimated load value is 30000 kN. For the test pile S1, when the load is loaded to 32000kN, the upper pile will be lifted, test pile is destroyed, and the load is terminated, so the load value for the upper and the lower parts of S1 test pile shall be 15000 kN; for test pile S2, when the load is loaded to 24000 kN, the upper pile will be lifted, test pile is destroyed, and the load is terminated, so the load value for the upper and the lower parts of S1 test pile shall be 11000kN. Test pile estimated load rating please see Table 3.

| Loading gradation | S1 Corresponding loading/MN | S2 Corresponding loading/MN | Loading gradation | S1 Corresponding loading/MN | S2 Corresponding loading/MN |
|-------------------|----------------------------|----------------------------|-------------------|----------------------------|----------------------------|
| 1                 | 2×2                        | 2×2                        | 9                 | 2×10                       | 2×10                       |
| 2                 | 2×3                        | 2×3                        | 10                | 2×11                       | 2×11                       |
| 3                 | 2×4                        | 2×4                        | 11                | 2×12                       | 2×12                       |
| 4                 | 2×5                        | 2×5                        | 12                | 2×13                       | 2×13                       |
| 5                 | 2×6                        | 2×6                        | 13                | 2×14                       | 2×0                        |
| 6                 | 2×7                        | 2×7                        | 14                | 2×15                       |                            |
| 7                 | 2×8                        | 2×8                        | 15                | 2×16                       |                            |
| 8                 | 2×9                        | 2×9                        | 16                | 2×0                        |                            |

Note: In the table, "0" in S1 and S2 corresponding loading indicates unloading.

3. Results of test pile

3.1. The curve results of test pile Q-S

The Q-S curve result of test pile S1 and S2 is shown in Figure 2 and Figure 3. It is known from the figures that: the Q-S curve of both the two test piles had a slowly varying type, of which, the maximum displacement of the upper and lower section of the pile is 41.15mm and 80.58mm respectively for the maximum loading value of S1 test pile; while the maximum displacement of the upper and lower section of the pile is 40.21mm and 42.60mm respectively for the maximum loading
value of S2 test pile. Due to the different geological conditions, pile length and the influence of balance point selection of both S1 and S2 test piles, the upper and lower section of the QS curve of test pile is not completely symmetrical; this phenomenon is quite common in practical engineering testing.

3.2. Test pile axial force and pile side friction test results

The axial force can be calculated through elastic modulus of steel and concrete, as well as their cross-sectional areas by a strain gauge, and the changes curve of axial force of each test pile under different load values along with the depth is shown in Fig 4. The figure shows that the axial force of pile at the same cross-section increases gradually along with the increase of load value; under the condition of different levels of preloading, the axial force distribution law is similar, and the axial force amplitude is close; but under the condition of same loading, axial force transmitted and decreased from the bottom to top along with the loading box position; in addition, the axial force at pile tip approaches to zero.

Figure 4. Distribution curve of S2 test pile axial force

Figure 5. Distribution curve of S1 test piles side friction resistance

Pile side friction resistance can be obtained with the ratio between the axial force difference of two adjacent steel strain gauges and the pile side area, under different levels of loading, the distribution curve of average pile side friction resistance of different sections is shown in Figure 5. The results showed that based on the differences in the nature of each rock-soil layer at a test pile, the pile side friction gradually increases with the increase of load value, and the increase amplitude is similar; however, the friction resistance of S1 test piles suddenly increased at the elevation of 164.12~162.32m (medium-weathered sandstone), the maximum friction resistance reaches to 570KPa, indicating that the pile side friction resistance is greatly influenced by the nature of rock-soil layer, the higher strength the pile geotechnical layer, the larger the role of pile side friction resistance; The rock-soil layer of pile side friction resistance at loading box plays the role first, and then the degree of role decreases from near to far, the minimum value is at the pile tip. While designing the rock-socketed pile, the upper part of side friction resistance value can be reduced appropriately.

Figure 6. Each rock-soil layer friction resistance of S1, S2 test pile
From Figure 6 we know that, the amount of pile compression and displacement increases along with the progressively increase of load, so does the side friction resistance of each rock layer, and the maximum side friction resistance is near the loading box; soil layer of friction resistance at the distance pile showed linear homogeneous changes; influenced by the axial force distribution and Poisson ratio effect, friction resistance of side rock layer increases along with the load, but not in linear changes. When the soil displacement of S1 test pile reaches to about 8mm, pile side friction resistance is stabilized. The side total resistance of S1 and S2 piles is 13099kN and 9522kN, respectively.

3.3. Pile tip resistance of test pile
As known from Figure 7 that the pile tip resistance increases along with the increase of load, so does the increase amplitude. The resistance close to zero when the load at pile tip is relatively small; tip resistance of embedded rock piles S1 and S2 test pile accounted for 53.4% and 53.6% of the pile bearing capacity, while the total side resistance accounted for 46.6% and 46.4% of the pile bearing capacity. Each test pile can give full play to the tip resistance and side friction resistance, and meet the design requirements.

3.4. Determination of the ultimate bearing capacity
Through equivalent conversion calculation, and based on the conversion between each rock-soil layer friction resistance and displacement measured value, we can obtain each test pile’s loading equivalent conversion curve, as shown in Figure 8. The figure shows: The load - displacement curve changes of S1, S2 test piles are more gentle, no significant turning point; so the ultimate load value of the last level is taken. In addition, the limit bearing capacity of S1, S2 piles is 28099kN and 20522kN, respectively, and the corresponding displacement is 70.96mm and 35.74mm, respectively.

4. Conclusion
The application and research of self-balanced method at the rock-socketed filling piles foundations of high-pile wharf at Inland River can be summarized in the following points:

Pile bearing capacity of rock-socketed filling piles in this project has met the design requirements. The vertical bearing properties of foundation piles indicate that, the pile tip resistance of rock-socketed pile S1 and S2 test piles accounted for 53.4% and 53.6% of the pile bearing capacity, while the total pile side resistance accounted for 46.6% and 46.4% of the pile bearing capacity, each test pile can give full play to their tip resistance and side friction resistance.

The soil-level friction resistance of pile side showed a linear and uniform distribution, influenced by the axial force distribution and Poisson's ratio effect, the friction resistance of tip rock-level friction continued to increase along with the load, but not in linear changes. When the soil displacement of S1
test pile reached to about 8mm, pile side friction resistance is stabilized. During the rock-socketed filling pile design, it is recommend that the value of upper side friction resistance value can be appropriately reduced.

Through the self-balanced method that conducted on the bearing property of rock-socketed filling piles of high-pile wharf at Inland River, it has verified the design reasonability and provided basis for the optimization of high-pile wharf type, which can not only reduce the construction cost of pier, but also provide reference for the similar large diameter rock-socketed filling piles of high-pile wharf at Inland River.

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