Comparative study on compressive and uplift load tests of PHC pipe pile

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Abstract. There are 5~8 m thick non self weight collapsible loess in the project site of a power plant. In order to study the bearing relationship between compressive and uplift piles in loess site, static load tests were carried out on PHC pipe piles with diameter of 400 mm and 500 mm and pile length of 12 m. Under the same pile top load, the displacement of uplift pile top is greater than that of compression pile top. Based on the measured load displacement curve, the uplift bearing capacity of PHC pipe pile with pile diameter of 500 mm is 32.5% higher than that of pile diameter of 400 mm. When the pile diameter is 400 mm and 500 mm respectively, the ultimate bearing capacity of PHC uplift pile is 26.24% and 27.70% of compression pile respectively. GM (1,1) model of grey system can fit and predict the load displacement curve of PHC pipe pile under compression and pull-out. Compared with the measured results, the relative error of GM (1,1) model of grey system is larger in the previous stages of load, and decreases gradually with the increase of load.

1. Introduction

With the gradual improvement of the height and complexity of structures, the requirements of various projects on the bearing capacity and settlement of pile foundation are also higher and higher. Various pile forming techniques and construction methods are constantly emerging. PHC pipe pile has high bearing capacity and has been widely used in various geotechnical engineering. In order to effectively reduce the total settlement and uneven settlement of buildings, it is necessary to study and predict the deformation of single pile. Jiang Jianping [1] used the modified hyperbolic model to fit the load displacement curve of uplift piles. The error between the fitting results and the measured values is within ±2.82%, which is more accurate and reliable. Ou Yangming [2] analyzed the existing mathematical model prediction methods, optimized the exponential curve model, and proposed a new modified exponential curve model, which can accurately describe the P-S curve of single pile. Based on the load transfer method, Liu Zhong [3] obtained the analytical solution of load settlement relationship of single pile for the whole process of pile-soil deformation through the double broken line load transfer function of pile-soil interaction. Wang Teng [4] analyzed the pile load displacement curve of the variation of the lateral friction resistance of the sand soil, obtained the analytical expression of the internal force of the pile body and the node displacement under three states of the pile side soil, and recursively obtained the relationship between the pile top load displacement. Wang Duanduan [5] predicted the ultimate bearing capacity of single pile combined with the law of load transfer along the pile body, studied the bearing performance of rotary bored pile, and fitted the load settlement curve with hyperbolic method, and the fitting effect was good. Gao Wenjing [6] proposed a unified trilinear load transfer model considering the pile side, pile tip elastic stage, plastic stage and
slip stage, and obtained the analytical solution of settlement curve which can fit nine load settlement relationships. Zheng Chen [7] used hyperbolic function and modified hyperbolic model to predict the load settlement curve of rock socketed PHC pipe pile, and pointed out that the accuracy of the modified hyperbolic model is higher than that of the modified hyperbolic model. Bao Yanran [8] fitted the curve of pile side friction resistance relative displacement of single pile by hyperbolic function of deformation, and pointed out that hyperbolic function of deformation is more accurate than hyperbolic function model in fitting \( \tau - S \) curve. In addition to the above load transfer method, Jiang Jianping [9] selected Weibull mathematical model to describe the uplift load displacement curve of PHC uplift pile according to the bearing characteristics of uplift PHC pile, and the fitting results are more accurate and reliable.

The load transfer function of single pile under the corresponding engineering conditions has been widely used for settlement prediction. Through the static load test of PHC pipe pile in a power station project, the law between the bearing characteristics of PHC pipe pile under compression and uplift is studied, and the fitting prediction is carried out through the pressure and uplift load displacement curve of two function models, which provides a theoretical basis for the design and construction of PHC pipe pile project.

2. Project overview

2.1 Site foundation soil conditions

Loess soil with different thickness exists in the site soil layer, the thickness is generally between 5 m and 8 m, and the soil layer is generally collapsible. The upper soil layer is grade I non gravity collapsible loess soil, and the characteristic value of foundation bearing capacity is 100 ~ 130 kPa. The engineering geological distribution is shown in Table 1.

The depth of water level survey in the area is generally about 15-25 m. It is mainly pore phreatic water. Due to the barrier of layer ③ silty clay, some boreholes expose the confined water in the lower part, and the groundwater level is deep. The station site is a non gravity collapsible loess site.

The average compressibility coefficients of layer ①① loess-like silt and layer ①2 loess-like silty clay are 0.24 and 0.41, respectively. They are both moderately compressible and relatively stable. They are non-weight collapsible loess, and the collapsibility grade is I. But the mechanical properties are different. ②1 layer of fine sand is slightly dense, thin in thickness, discontinuous in distribution, and low in mechanical strength. ②2 layer of fine sand and medium-coarse sand is medium-dense to dense, with stable layer position, relatively uniform, high mechanical strength, and a good foundation supporting layer; but attention should be paid to layer ②3 silty clay and silt, which are plastic and slightly. It is dense and produces lenticular shape with uneven distribution. The ③ layer silty clay is plastic to hard plastic with high mechanical strength. In order to eliminate the collapsibility of the site, the pipe pile is used for treatment. The pile end enters into the ②2 layers of fine sand, medium sand and coarse sand as the pile end bearing layer.

### Table 1. Engineering geological distribution

| Soil layer number | Soil layer name | Layer thickness/m | End resistance of CPT/MPa | Corrected blow count of standard penetration test |
|-------------------|----------------|-------------------|--------------------------|--------------------------------------------------|
| ①1               | Loess like silt | 3.9~6.7           | 0.35~2.28                | 3.8~12.3                                          |
| ①2               | Loess like silty clay | 0.7~1.2         | 0.35~0.76                | 2.0~5.9                                           |
| ②1               | Fine sand       | 0.4~1.3           | 0.92~16.62               | 6.1~13.6                                          |
| ②2               | Fine sand medium coarse sand and coarse sand | —                  | 2.16~33.39               | 13.1~39.0                                        |
| ②3               | Silty clay      | 0.3~1.2           | 0.45~14.59               | —                                                 |
| ③                | Silty clay      | 2.0~4.0           | —                        | 10.4~18.0                                         |

2.2 General situation of static load test

T12 PHC pipe piles are selected for the site, with concrete strength of C80, pile diameter of 400 mm and 500 mm, and pile length of 12 m.
(1) Three PHC compression piles with pile diameter of 400 mm are S1, S4 and S5, and three uplift piles are S2, S3 and S6.

(2) Three PHC compression piles with pile diameter of 500 mm are S7, S8 and S9, and three uplift piles are S10, S11 and S12.

Before and after the static load test, the low strain integrity test of the test pile is carried out. Before the vertical static load test, the pile body is complete, and the integrity of the pile body meets the design requirements.

3. Analysis of test results

Figure 1 shows the load (P) ~ displacement (S) curves of PHC Piles with diameter of 400 mm and 500 mm respectively. According to figure 1, when the vertical load of test pile S1 is increased to 2000 kN, the pile body concrete at the top of the pile is suddenly damaged and can not be loaded continuously. When the vertical load of S4 and S5 is increased to 2640 kN and 2750 kN respectively, the settlement reaches 79.06 mm and 78.66 mm respectively, so the load can not be maintained, so it is no longer loaded. When the vertical load of S7, S8 and S9 is increased to 2700 kN, 3000 kN and 3000 kN respectively, longitudinal cracks appear in the pile body concrete at the top of the pile, and the cracks continue to increase, so the test is terminated.

When PHC compressive pipe pile meets the requirements that the pile end enters into the ② layers of fine sand, medium sand and coarse sand as the pile end bearing layer, the depth into the bearing layer is about 4 m, and the final penetration meets the requirements of 20 ~ 40 mm and the same pile cutting condition, the average vertical compressive ultimate bearing capacity of single pile of Φ 400 mm test pile is 2066 kN, and the average value of bearing capacity characteristic value is 1033.3 kN. The average value of vertical compressive ultimate bearing capacity of single pile of Φ 500 mm test pile is 2600 kN, and the average value of bearing capacity characteristic value is 1300 kN, which is 25.8% higher than that of Φ 400 mm PHC pipe pile.

According to Fig. 2, S2, S3 and S4, when the vertical load is increased to 600 kN, the reinforcement is broken, and the test can not be continued and the test is terminated. When the vertical load of S10, S11 and S12 is increased to 800 kN, the longitudinal cracks appear in the concrete of pile top and pile body, and the test is terminated. For PHC uplift pipe pile, the standard value of Uplift Ultimate Bearing Capacity of single pile of Φ 400 mm pile is 543 kN, and the characteristic value of vertical uplift bearing capacity of single pile is 271 kN under the condition that the pile end enters into the ② layers of fine sand, medium sand and coarse sand, and the depth of the bearing layer is about 4 m, and the final penetration meets the condition of 20 ~ 40 mm and the test pile is planted with reinforcement. The standard value of Uplift Ultimate Bearing Capacity of single pile of Φ 500 mm pile is 720 kN, and the corresponding characteristic value of vertical uplift bearing capacity of single pile is 360 kN, which is 32.5% higher than that of PHC pipe pile with Φ 400 mm.

When the pile diameter is 400 mm, the ultimate bearing capacity of uplift pile is 26.24% of that of compression pile; when the pile diameter is 500 mm, the ultimate bearing capacity of uplift pile is 27.70% of that of compression pile.

Under the same pile top load, the uplift of uplift pile is greater than the settlement of compression pile. When the load is small, the two kinds of test displacements are close to each other. With the increase of load, the difference between the two kinds of displacement gradually increases. When the pile diameter is 400 mm and 500 mm, when the uplift pile is loaded to 600 kN and 800 kN, the average displacement of the pile top is 17.1 mm and 18.7 mm respectively, and the average displacement of the corresponding compression pile top is 5.1 mm and 4.9 mm respectively; the pile top displacement corresponding to 400 mm and 500 mm pile diameter is 29.82% and 26.20% of the uplift pile top displacement. When the pile diameter is 400 mm and 500 mm, the corresponding load of the compression pile is 1575 kN and 2126 kN when the pile diameter is 400 mm and 500 mm respectively, and the load of the uplift pile is 38.02% and 37.59% of that of the compression pile respectively.
4. Prediction of Q–s curve of PHC pipe pile

Grey modeling [10] refers to the establishment of an approximate differential equation by analyzing and processing the sequence. The common prediction model is GM (1,1) model. The load displacement curve of PHC compression and uplift piles is predicted by GM (1,1) model. The comparison between the measured value and the predicted value of the Q-S curve of PHC compression pipe pile is shown in Figure 5-7.

The GM (1,1) model of grey system is used to predict the load displacement curves of PHC pipe piles under pressure and pulling out. The predicted results are in good agreement with the measured load displacement curves. Compared with the measured results, the relative error is larger in the first several stages of load, and decreases with the increase of load. Taking PHC compression pipe pile S1 as an example, the relative error of the first load is 40.7%, while that of the last load is 2.9%; taking S2 of PHC uplift pipe pile as an example, the relative error of the first load is 227.6%, while the relative error of the last load is 28.1%. The main reason for the larger displacement error of the first several loads is that the displacement value corresponding to the first several levels of load is small.
5. Conclusion

(1) The failure form of PHC pipe pile in this site is the concrete failure of pile top and pile body. The maximum settlement of pile top is small, or the settlement of pile is too large to continue to bear the load. The maximum settlement of pile top is large. The failure modes of PHC piles are as follows: the reinforcement at the top of the pile is broken or the concrete on the top of the pile appears longitudinal cracks.

(2) Under the same pile top load, the uplift of uplift pile is greater than the settlement of compression pile. When the pile diameter is 400 mm and 500 mm, the corresponding load of the compression pile is 1575 kN and 2126 kN respectively when the pile diameter is 400 mm and 500 mm, and the load of the uplift pile is 38.02% and 37.59% of the corresponding load of the two pile diameters.

(3) When the pile diameter is 400 mm, the ultimate bearing capacity of uplift pile is 26.24% of that of compression pile; when the pile diameter is 500 mm, the ultimate bearing capacity of compression pile is 27.70% of that of uplift pile.

(4) GM (1,1) model of grey system can fit and predict the load displacement curves of PHC pipe piles under compression and pulling out. Compared with the measured results, the relative error of GM (1,1) model of grey system is larger than that of the former load, and the relative error decreases with the increase of load.

References

[1] Jiang Jianping, Gao Guangyun, Liu Wenbai. Study on the modified hyperbolic model to describe the Q-S curve of the piles [J]. Journal of Basic Science and Engineering, 2010, 18(06): 999-1009.
[2] Ou Yangming, Ding Boyang, Shi Jiseng. Study on the fitting of modified exponential curve model of load settlement curve of single pile [J]. Port & Waterway Engineering, 2013(01): 31-38.

[3] Liu Zhong, Tang Yang, Du Huanghuan, Zhu Sijing, Peng Gang. Settlement analysis of single pile based on load transfer method [J]. Journal of Xiangtan University(Natural Science Edition), 2013, 35(02): 35-40.

[4] Wang Teng, Lu Shuqin, Chen Jinxia, Shen Yuanyuan. Analytical solution of pile foundation load settlement based on multi section load transfer method [J]. Journal of Shenyang Jianzhu University(Natural Science), 2015, 31(03): 442-448.

[5] Wang Duanduan, Zhang Xingming, Zhou Zhijun, Zhang Lipeng. Study on load transfer characteristics of rotary drilling pile in loess area of Northern Shaanxi Province [J]. Journal of Railway Science and Engineering, 2016, 13(07): 1268-1274.

[6] Gao Wenjin, Li Wenju, Zhang Fugui. Analysis and application of unified three fold line model of single pile load transfer method [J]. Building Structure, 2017, 47(S1): 1059-1066.

[7] Zheng Chen, Bai Xiaoyu, Zhang Mingyi, Miao Dezi. Study on static load test and load settlement curve model of rock socketed PHC pile [J]. Journal of Guangxi University(Natural Science Edition), 2019, 44(02): 516-523.

[8] Bao Yanran, Ma Hailong, Lei Shanshan. Test curve of pile side friction and pile-soil relative displacement and its fitting analysis [J]. Journal of Zhejiang Sci-Tech University(Natural Sciences Edition), 2020, 43(01): 102-108.

[9] Jiang Jianping, Gao Wenyun, Liu Wenbai. Weibull mathematical model for describing the uplift load displacement curve of PHC pile [J]. Advanced Engineering Sciences, 2009, 41(04): 82-88.

[10] Du Guangyin, Huang Feng, Li Guangxin. Study on side resistance of compression pile and uplift pile [J].Journal of Engineering Geology, 2000(01): 91-93.