Study on bearing performance of mixed pile on saturated silty sand ground

Fengyi Tan i), Hanbing Hu i), Wenzhi Lv ii), iii), Jiali Ren i) and Lin Hu iii)

i) Senior Engineer, Yangtze River scientific Research Institute, Wuhan 430015, China.
ii) Senior Engineer, Dalian Wanda Commercial Properties Co., Ltd, Beijing 100022, China.
iii) Senior Engineer, Wuhan Changke Engineering Construction Supervision Co., Wuhan 430015, China.

ABSTRACT

The Quaternary alluvial deposits was widely distributed in the field of hydropower station, composed of the silty sand with mud, the silty sand and the gravel. The Quaternary alluvial was with the low average standard compaction number and the loose structure, high compressibility and low bearing capacity, particularly its saturated silty sand had the potentiality of liquefaction. According to these characteristics, the single mixed pile foundation was used to improve its bearing performance. There were series of static loading tests in situ with the different conditions including the three different pile’s length and the two different bearing stratum. Combined with the data of numerical analysis, its failure modes were analyzed and both of the vertical ultimate bearing capacity and the characteristic value of bearing capacity were obtained. Study showed that: 1) when bearing stratum was the compacted sands or the gravel, the P-S curve was the gradually falling type with no steep drop and the P-△s/△P curve had plain stage or sharp, 2) when pile length was 14.0m and 19.0m respectively, the pile failuer was resulted by the pile flaw, their ultimate bearing capacity by the static loading test was lower than the ultimate strength value of core of pile and the one calculated by the minimum combination, when pile length was 11.0m, it was controlled by the ultimate bearing capacity by the resistance from the soil surround pile and the resistance from the pile’s tip. The study was the foundation for the follow up tests of grid structure mixed pile composite foundation and as the reference for the similar engineering.

Keywords: saturated silty sand, mixed pile, static loading test, numerical analysis, bearing performance

1 INTRODUCTION

The Quaternary alluvial deposits was widely distributed in the field of hydropower station, composed of the silty sand with mud, the silty sand and the gravel, in which the silty sand layer was the ground of the main structure of hydropower station with the 20.0m in depth. For this layer, its average standard compaction number was just 8, meanwhile it had the loose structure, high compressibility and low bearing capacity, the dam site engineering geological report showed that the liquefaction would be happened under the condition of earthquake with 6.0 degree. According to these characteristics, the mixed pile foundation was used to improve its bearing performance.

The mixed pile was the cement-soil consolidation forming with certain strength and the low permeability over a period of time, in which the curing agent such as the cement was mixed with the soil by the special mixing machine. Due to the cement-soil consolidation, the physical and mechanical property of ground was enhanced and it was formed the composite foundation with high deformation modulus and bearing performance. According to the different construction methods, there were two different methods of the cement-soil mixing, the cement slurry method and the dry jet mixing method (Gong 1993 and 2002).

The mixed pile belonged to the non-replacement pile with the following engineering properties: flexible layout, low permeability and water proof, adjustable distance between piles, adjustable cement ratio according to the engineering requirement and soil property, fast construction progress, and low construction cost, etc. (Chen 2007). It was widely used in the soft clay or silts to enhance their bearing performance, stability and deformation (China 2012).

At present, the mixed pile was used as the composite foundation combined with other types of pile, its bearing performance was studied by the laboratory test and the numerical analysis and abundant
achievement was obtained (Duan 2002, Lei 2003, Lv 2009a and 2010, Qiu 2001, Rao 2002, Shi 2002, Tan 2006 2011a and 2011b, Wang 2003, Wen 2008a and 2008b, Wu 2007, Yangtze 2005, Zhou 1997).

But it was regretful that the bearing performance of mixed pile mainly depended on the laboratory test, particularly the numerical analysis, which indicated that there are few data of in situ test due to its high cost, time consuming and the influence of construction. But for numerical analysis, the material of pile was the ideal homogeneous mass that conflicted with the heterogeneous material of pile in engineering, furthermore the condition and parameter setting in the numerical analysis wasn’t in accordance with the engineering.

Based on the full scale static loading test in construction site combined with the related numerical analysis, the bearing performance of single mixed pile in the saturated silty sand ground was studied. First for the tests, there were two different factors: one was the different pile’s length with 11.0m, 14.0m and 19.0m, the other was the different bearing stratum with the silty layer and the gravel layer. Then there was the numerical analysis based on the related full scale static loading test, the bearing performance and failure characteristics of single mixed pile was analyzed, which was the foundation for the follow up tests of grid structural mixed pile foundation and as the reference for the similar engineering.

2 FULL SCALE STATIC LOADING TEST IN CONSTRUCTION SITE

2.1 Test arrangement

The low floodplain of left bank of hydropower station was chosen as the test region, the parameters and the layout was shown in Table 1 and Fig.1, respectively.

| Test ID | Pile length(m) | Area (m²) | Pile diameter(m) |
|---------|----------------|-----------|-----------------|
| D1D2D3 | 11             |           |                 |
| D4D5D6 | 14             | 0.283     | 0.6             |
| D7D8D9 | 19             |           |                 |

![Fig.1 Layout for full scale static loading test](image)

2.2 Test method

During the test there was the slow loading and the loading was applied at least from 8 to 10 levels according to the estimated bearing capacity, the next loading wasn’t applied until the settlement was no more than 0.1mm/h.

When one of the following conditions was satisfied, the static loading test was terminated: (1) the settlement at this level was no less than 5 times compared with that at the earlier level, (2) the total settlement was more than 40.00mm when there was the steep drop type of the P-S curve or the total settlement was controlled within from 60.0mm to 80.0mm when there was the gradually falling type of the P-S curve.

For the P-S curve the value of the beginning of steep descending was chosen as the ultimate bearing capacity, the characteristic value of the vertical bearing capacity of single pile was the minimum between the half of ultimate bearing capacity and the scale threshold value.

2.3 Result analysis

There was the compressive deformation both of the pile’s top and upper part under the loading was applied onto the bearing plate, then there was the shaft resistance between the pile and the soil surrounded pile, as a result, the axial force of pile reduced to zero, the shaft resistance on the pile’s body, where the axial force was zero, didn’t play a role, correspondingly the pile settlement was increased steadily, which was the straight segment both of P-S and P-△s/△P curves, shown in Fig.2 and Fig.3.

With the increasing of the loading on the bearing plate, if there was the flaw on the top of pile or the low strength of pile due to design, the loading was exceeded the cement-soil resistance (the unconfined compressive strength), the top of pile was crushed or fractured, the failure of pile belonged to the brittle failure, correspondingly the bearing plate settled suddenly and its settlement was non convergence, which was the steep drop both of P-S and P-△s/△P curves, shown in Fig.2 and Fig.3. For the whole curves both of P-S and P-△s/△P, there were two straight line segments or no obvious transition curve segments, which indicated that the bearing capacity of pile was controlled by the pile strength, and there is the effective pile length.

If the quality of pile was good and it had sufficient strength, the axial force of pile was transit to the underpart of pile until to the tip of pile with the increasing of loading on the bearing plate, which indicated that the straight line segment both of P-S and P-△s/△P curves is ended. The most of further increasing loading on the bearing plate was borne from the pile’s shaft resistance to tip resistance, which indicated that the pile’s behavior is influenced by the pile tip soil, correspondingly, the bearing performance of mixed pile is controlled both by the pile shaft resistance and tip resistance.
For the static loading tests, the bearing stratum was the compacted sands when the pile length was 11.0m and 14.0m respectively or the gavel when the pile length was 19.0m. When the loading of bearing plate was applied and increased continuously, the bearing stratum was compacted to increase its bearing performance and had different adjustment stages, at last, the compacted sands was failure and the ultimate vertical bearing capacity of single mixed pile was controlled by the residual strength. During the whole process, the P-S curve was the gradually falling type with no steep drop, but for the P-\(\Delta s/\Delta P\) curve, during the process of the sands or gravel was compacted and their strength was increased, it had plain stage or sharp, which indicated that the settlement was increased gradually or steeply.

Fig.2 and Fig.3 were the P-S and P-\(\Delta s/\Delta P\) curves, and the results analysis was shown in Table 2.

### 3 NUMERICAL ANALYSIS

Numerical calculation scope for the initial geostress of soil: length was 120.0m, width was 60.0m and depth was 75.0m, the altitude of the top of pile was 26.5m, the altitude of the top of gravel was 7.5m and it was 35.4m thickness in depth, under the gravel there was malmstone.

Boundary condition: there were no lateral displacement and settlement under the bottom and the normal constraint on the lateral.

Constitutive model: the studied showed that the reasonable simulation of deformation behaviors both of the silty sands and gravel played an important role to make sure the accuracy and reliability of prediction of the whole structural deformation, particularly it was proved by the amount of trixial tests that the Duncan model would reflect properly the non-linear property both of the silty sands and gravel, therefore the Duncan E-B non-linear model was used to reflect the relationship between stress and strain both of the silty sands and gravel in the numerical simulation.

The contact model: when the friction property of the contact interface was considered, its friction related with the following factors, such as the size of contact force, the smoothness of interface, the property of materials, the relative stiffness of contact pair. In the simulation, the Mohr-Coulomb was adopted, in which the coefficient of friction \(f\) was used to describe the friction behavior of contact interface, and \(f\) was 0.45.

Parameters: all parameters were shown in Table 3, particularly, the coefficient of friction between pile and
soil was 0.45, the malmstone was simulated by the linear elastic constitutive model, in which dry density was 1.96 g/cm³, deformation modulus was 30.0MPa, poisons ratio was 0.35.

In the numerical simulation, the FEM software ABAQUS was used.

Table 3 Parameters of soil and cement mixed pile

| Material                  | \( r \) (g/cm³) | \( \varphi \) (°) | \( \Delta \varphi \) (°) | \( C \) (kPa) | \( R_f \) | \( k \)   | \( n \)   | \( K_{ur} \) | \( k_b \) | \( m \) |
|--------------------------|-----------------|-----------------|-----------------|-------------|--------|--------|--------|--------|--------|------|
| Cement mixed pile        | 1.92            | 38.7            | 848             | 0.32        | 4899.3 | 0.49   | 9800   | 1712   | 0.46   |
| Silty sands              | 1.85            | 35.3            | 0.025           | 0.802       | 310    | 0.46   | 600    | 155    | 0.27   |
| Malmstone                | 2.14            |                 |                 |             |        |        |        |        |        |

3.1 Simulation result

The result both of tests and simulation was shown in Table 4 and Fig.4 to Fig.6.

Table 4 P-S Statistic both of tests and simulations

| Test ID | Loading P(MPa) | test results (mm) | simulation results(mm) | Error (mm) |
|---------|----------------|-------------------|------------------------|------------|
| D3 pile | 0.00           | 0.00              | 0.0                    | 0.0        |
|         | 0.61           | 1.41              | 2.4                    | 0.99       |
|         | 0.91           | 5.02              | 3.6                    | 1.42       |
| 11.0m   | 1.21           | 9.03              | 4.7                    | 4.33       |
| length  | 1.52           | 16.16             | 5.9                    | 10.30      |
|         | 1.82           | 28.37             | 7.0                    | 21.4       |
|         | 0.00           | 0.00              | 0.0                    | 0.0        |
| D4 pile | 0.75           | 1.66              | 2.9                    | 1.24       |
|         | 1.13           | 3.97              | 4.4                    | 0.43       |
| 14.0m   | 1.50           | 7.37              | 5.7                    | 1.67       |
| length  | 1.88           | 11.07             | 7.1                    | 3.97       |
|         | 2.25           | 16.27             | 8.5                    | 7.77       |
| D8 pile | 0.00           | 0.00              | 0.0                    | 0.0        |
|         | 1.07           | 2.44              | 4.1                    | 1.66       |
| 19.0m   | 1.61           | 5.95              | 6.1                    | 0.15       |
| length  | 2.14           | 14.62             | 8.1                    | 6.52       |

Table 4 and Fig.4 to Fig.6 showed that there was obvious difference for settlements that was from tests and simulations, particularly under the heavy loading condition, the settlement from tests was bigger than the one of simulation. When it showed that it was the ultimate vertical bearing capacity of the P-S curve from tests, but it was still in the linear elastic stage of the P-S from simulations.
3.2 Simulation result analysis

For the single pile, there were some flaws more or less due to the mixed pile construction technology. At the beginning of loading in the static loading test, it was also the low stress level, the pile's flaw couldn’t result in the pile’s failure, therefore, there was a strong relationship between the tests results and the simulation ones. But with the increasing and further increasing of loading and stress level, the pile’s flaw could result in the pile’s failure in sudden, which was reflected from the P-S curve of tests that there was the steep drop, on the other hand, there was the the ideal homogeneous mass of pile in the simulation, as a result, the following factors related to the non homogeneous mass wasn’t simulated including crack, void, richful sand part in pile and broken pile, etc..

4 THE BEARING PERFORMANCE OF MIXED PILE IN SANDS

According to the Technical code for ground treatment of buildings, the characteristic value of the vertical bearing performance of a single pile should be obtained by the static loading test. For the preliminary design stage, it was also calculated by equation (1), meanwhile it must be satisfied with the equation (2), that was the bearing capacity of single pile from the pile strength shouldn’t be no less than the one from the resistance force both from the soil surround pile and the soil under the pile’s tip.

\[ R_u = u \sum_{i=1}^{n} q_i l_i + \alpha q_p A_p \]  
(1)

\[ R_u = \eta f_{cu} A_p \]  
(2)

In equation, \( f_{cu} \) -- the average value of cubic compressive strength after 90 days of standard maintenance(kPa), \( \alpha \) --reduction coefficient of pile’s strength, for the cement slurry method, \( \eta \) was about 0.25-0.33. \( q_p \) -- the unamended characteristic value of the vertical bearing performance of single pile’s tip (kPa), \( \alpha \) --reduction coefficient of bearing capacity of pile’s tip, about 0.4-0.6, if the bearing capacity was higher, 0.4 was adopted.

According to the equation (1), when the shaft resistance and the pile’s tip resistance were chosen, the bearing capacity of single pile was obtained under the certain diameter and length. If the minimum combination both of the range of shaft resistance of soil surround pile and the range of resistance of soil under the pile tip, the minimum bearing capacity of single pile was obtained, which was provided by both of the resistance from the soil surround pile and the resistance from the pile’s tip. If the minimum bearing capacity was more than the bearing capacity provided by pile’s strength, the bearing capacity from the static loading test was controlled by the pile’s strength. The mechanical index of ground was shown in Table 5 and the minimum combination was chosen: the characteristic value of the shaft resistance was 12.0kPa, the bearing capacity of silty sands was 120.0kPa when pile length was 11.0m and 14.0m, the bearing capacity of gravel was 340.0kPa when pile length was 19.0m, then the bearing capacity of single pile was shown in Table 6.

| Range of characteristi c value | Shaft resistanc e (close) | Shaft resistanc e (middle density) | Bearing capacity of soil surroun d pile | Bearing capacit y of soil under pile tip |
|--------------------------------|---------------------------|-----------------------------------|----------------------------------------|----------------------------------------|
| 10-25                          | 20-35                     | 120-180                           | 300-40                                 |

Table 6 bearing capacity of single pile

| Pile ID | Length (m) | characteristic value of shaft resistance (kPa) | \( q_p \) | Bearing capacity of single pile (kN) | \( f_{cu} \) (kPa) | Axial bearing Capacity (kN) | Ultimate bearing capacity by static loading test (kN) |
|---------|------------|-----------------------------------------------|--------|----------------------------------|----------------|---------------------------|----------------------------------|
| D1-D3   | 11.0       | 12.0                                          | 120    | 524.8                            | 6290           | 1185                      | 515                              |
| D4-D6   | 14.0       | 12.0                                          | 120    | 660.5                            | 6290           | 1185                      | 637                              |
| D8-D9   | 19.0       | 12.0                                          | 340    | 974.9                            | 6290           | 1185                      | 600                              |

In Table 6: (1) The bearing capacity of single pile was calculated from the resistance from the soil surround pile and the resistance from the pile’s tip ; (2) \( f_{cu} \) was 6.29MPa, the standard value of core of pile (3) for the axial bearing capacity calculation, the reduction coefficient of pile’s strength was 0.33(4)the value of ultimate bearing capacity by static loading test was the one related to the beginning of steep drop of P-S curve, if the pile flaw was considered, it was the maximum when the pile length was same.

Table 6 showed that the ultimate bearing capacity by the static loading test, when pile length was 14.0m
and 19.0m respectively, was lower than the ultimate strength value of core of pile and it was also lower than the one calculated by the minimum combination, it reflected that the pile failure was resulted by the pile flaw. Considered the P-S curve of static loading test, the ultimate bearing capacity of single pile, when pile length was 11.0m, was controlled by the ultimate bearing capacity by the resistance from the soil surround pile and the resistance from the pile’s tip.

5 Conclusion

There were series of static loading tests in situ with the different conditions including the three different pile’s length and the two different bearing stratum. Combined with the data of numerical analysis, its failure modes were analyzed and both of the vertical ultimate bearing capacity and the characteristic value of bearing capacity were obtained. The study showed that:

1) when bearing stratum was the compacted sands or the gravel, the P-S curve was the gradually falling type with no steep drop and the P-△s/△P curve had plain stage or sharp because the bearing stratum was compacted to increase its bearing performance and had different adjustment stages, at last, the compacted sands was failure and the ultimate vertical bearing capacity of single mixed pile was controlled by the residual strength.

2) when pile length was 14.0m and 19.0m respectively, the pile failure was resulted by the pile flaw, their ultimate bearing capacity by the static loading test was lower than the ultimate strength value of core of pile and the one calculated by the minimum combination, when pile length was 11.0m, it was controlled by the ultimate bearing capacity by the resistance from the soil surround pile and the resistance from the pile’s tip.

REFERENCES

1) Chen, S. and Chen, G. (2007): Study on the cement soil pile composite foundation, Journal of China & Foreign Highway, 27(3), 34-41(in Chinese).
2) China Academy of Building Research (2012): Technical code for ground treatment of buildings, CHINA ARCHITECTURE & BUILDING PRESS (in Chinese).
3) Duan, J. (1993): Numerical analysis of flexible pile composite foundation, Zhenjiang University.
4) Gong, X. (1993): Deep mixing method design and construction, CHINA RAILWAY PUBLISHING HOUSE (in Chinese).
5) Gong, X. (2002): Composite foundation theory and application in engineering, ISBN 9787112052998, CHINA ARCHITECTURE & BUILDING PRESS (in Chinese).
6) Lei, X. and Tan, F. (2003): Finite element analysis on bearing performance of DJM single- pile composite foundation, Rock and Soil Mechanics, 24(supp), 526-528.
7) Lv, W. (2009a): Study on the Working Behavior and Design Method of the Pile Composite under the Flexible Foundation, Zhejiang University.
8) Lv, W., Yu, J. and Lv, C. (2009b): Load transfer rule of composite ground under flexible foundation, China Journal of Highway and Transport, (6),1-9.
9) Lv, W., Yu, J. and Gong, X. (2010): Review of Experimental Studies on Composite Ground under Flexible Foundation, Journal of Highway and Transportation Research and Development, (1), 1-5.
10) Qiu, Y., Qian, G and Liu, S. (2001): DJM Pile Treated Soft Clay Foundation on Express Highway The Analysis of the Additional Stress in Composite Foundation and the Settlement of Composite Foundation, Journal of Highway and Transportation Research and Development, 18(1): 1~5.
11) Rao, X., Jiang, N. and Zhao, K. (2002): Countermeasures on geotechnical problems in strengthening construction of Changfeng sluice, Yangtze River, 33(8), 51-53.
12) Shi, J. and Zou, J. (2002): Study on calculative theory of settlement of composite ground reinforced by deep-mixing pile group, Rock and Soil Mechanics, 23(3), 309-315.
13) Tan, F., Hu, D. and Ding, Y. (2006): Numerical analysis of the settlement factor of the Multi-pile composite foundation, Rock and Soil Mechanics, 27(supp), 914-916.
14) Tan, F., Wang, R. and Zhao, L. (2011a): Numerical calculation for bearing performances of composite foundation improved by flexible piles, Rock and Soil Mechanics, 32(1), 288-292.
15) Tan, F. and Wang, X. (2011b): Numerical Analysis for Bearing Performance of Flexible Piles Composite Foundation Influenced by Modulus’ Changes. Advanced Materials Research, 261-263, 1694-1698.
16) Wang, X., Yu, Y. and Gao, W. (2003): Analysis on Additional Stress in Composite Foundation of DJM Pile under Flexible Load of Embankment, China Municipal Engineering, 23(3), 309-315.
17) Wen, S., Jiang, Z. and Zhang, M. (2008a): Settlement calculation and analysis of cement mixed pile composite foundation, Geotechnical Engineering World, 11(1), 1-4.
18) Wen, S. and Zhang, M. (2008b): Construction Technology Research of Cement Mixing Piles in Fine Sand Stratum, Soil Engineering and Foundation, 22(2), 13-16.
19) Wu, B. and Li, T. (2007): Calculation of compressive modulus of grid structure-composite foundation, Rock and Soil Mechanics, 28(10), 2183-2187.
20) Yangtze River scientific Research Institute (2005): Report of study on mixed pile composite foundation in Xinglong hydropower station.
21) Zhou, J., Feng, D. and Zhen, H. (1997): Finite Element Analysis for Compound Foundation of Deep Mixing Piles, Rock and Soil Mechanics, (2), 44-50.