Study on the bearing capacity of large diameter cast-in-place pile by using fiber optic testing technology

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Abstract. The project is located in Yantai, Shandong province, China, and consists of 5 buildings. The height of the north apartment is 122.7~133.5 m with 41~43 layers. The height of the south apartment is 127.9~133.7 m with 40~42 layers. The height of the hotel is 123.0 m with 32 layers. The height of the building podium is 17.3 m with 3 layers and an underground parking garage. The embedded depth of the foundation is 12.6 m. Natural foundation is adopted for podium and underground garage and pile foundation is adopted for other buildings.

According to the geotechnical investigation, the layers below the foundation elevation are Quaternary sedimentary soil layers, Proterozoic schist, quartzite, and gneissic granite. With the pile tip bearing stratum being strongly or moderately-weathered rock, three groups of test piles were arranged in the foundation to determine whether the pile bearing capacity can meet the design requirement of 11500 kN characteristic value. Test group 1 consisted of 3 piles (No. SZ01 to SZ03) with a diameter of 1.2 m. The pile tip of group 1 was into strongly weathered rock for 2.4 m with the pile length of 27.0~28.5 m. Test group 2 consisted of 3 piles (No. SZ04-SZ06) with a diameter of 1.2 m. The pile tip of group 2 was into moderately-weathered rock for 0.5 m with the pile length of 31.0 m. Test group 3 consisted of 1 pile (No. SZ07) with a diameter of 1.2 m. The pile tip of group 1 was into strongly weathered rock for 0.5 m with pile length of 27.0 m. The test piles are grouted at the bottom and side except No.SZ07.

The optical fiber was laid on No. SZ01 and No. SZ05 piles and tied to the reinforcing cage. The side friction resistance and tip resistance of piles under each load level were measured in the load test. The results showed that the pile tip resistance value accounted for only 1.82%~2.32% of the total load when the design bearing capacity characteristic value was 11500 kN load, and only accounted for 4.43%~9.92% of the total load when the ultimate bearing capacity was 23000 kN load, indicating that the pile tip resistance was not fully utilized. The load test results of 7 piles showed that the bearing capacity of a single pile met the characteristic value of 11500 kN.

According to the results of the load test, the design scheme of the pile foundation was optimized. The number of foundation piles was reduced from 274 to 244, and the bearing rock of pile tip was 2.4 m into strongly weathered layer, changing from the initial value of 2.4 m into moderately-weathered layer. The project was completed in November 2008 and is currently running well.

Key words: ultimate bearing capacity of a single pile; optical fiber test; load test.

1. Introduction

To meet the needs of structural load and building deformation control, pile foundation is often used in super high-rise buildings due to their complex shape and large load, such as China World Trade Center Tower 3[1] and China Zun[2,3] in Beijing. Although some super high-rise buildings adopt composite foundation with good effect, such as ICON Yunduan Tower in Chengdu[4] and a project in Guangxi[5], most super high-rise buildings still adopt pile foundation. However, the selection of the bearing stratum
at the pile end and the determination of lateral resistance and end resistance of piles are important issues of the pile foundation. To determine the lateral resistance of piles, the steel stress meter was often used for testing\cite{6}. In the recent years, with the development of optical fiber technology, the optical fiber sensors with the advantages of small size, corrosion resistance, high sensitivity, and distributed measurement have been widely used in pile foundation engineering\cite{7,9}. The paper describes optical fiber testing and optimization of pile foundation conducted by our institute in a project located in Yantai City, Shandong Province, China.

2. Project overview and layout of test piles

2.1 General Situation of the Buildings

The building is located in Yantai City, the general situation of the buildings is shown in Table 1. Due to the high characteristic value of the ultimate bearing capacity (23000 kN) of a single pile, the ordinary cast-in-place pile is difficult to meet the bearing capacity requirements, thus rock-socketed piles are adopted in the preliminary design of the design institute. The pile diameter is 1.2 m, and the pile end is embedded into the moderately-weathered layer for 2.40 m. The rock-socketed piles are characterized by great difficulty in construction, long construction period, and high cost. On studying the strata in the investigation report and consulting with the owner and the design institute, we decided to adopt the post-grouting technology of cast-in-place piles to meet the requirements of bearing capacity and settlement with less piles and short pile length. This technology is applied for the first time in Yantai City, thus it is necessary to do a pile test before the formal construction of pile foundation.

Table 1. General situation of buildings

| Building name                  | North apartment | South apartment | Hotel | Hotel podium | Underground garage |
|--------------------------------|-----------------|-----------------|-------|--------------|--------------------|
| Height (m)                     | 122.7~133.5     | 127.9~133.7     | 123.0 | 17.3         | /                  |
| Number of storeys              | 41~43           | 40~42           | 32    | 3.0          | /                  |
| Basement                       | 2               | 2               | 2     | 2            | 2                  |
| Depth of foundation (m)        | 12.6            | 12.6            | 12.6  | 12.6         | 12.6               |
| Foundation form                | Pile foundation | Pile foundation | Pile foundation | Natural foundation | Natural foundation |
| Quk (kN)                       | 23000           | 23000           | 23000 | /            | /                  |

Note: $Q_{uk}$ depicts the value of the ultimate bearing capacity of a single pile;

2.2 The Test Piles

The test piles are arranged in the underground garage (Fig. 1). In Fig. 1, SZ represents the test pile and MZ represents the anchor pile. Considering that the bearing stratum at pile end varies from heavily-weathered layer to moderately-weathered layer, 3 groups of test piles are arranged and the parameters of each group are shown in Table 2.

Table 2. Parameters of test piles

| Pile no. | Pile diameter (m) | Pile length (m) | Bearing stratum at pile end | $Q_{uk}$ (kN) | Grouting |
|----------|-------------------|-----------------|----------------------------|---------------|----------|
| SZ01     | 1.2               | 27.0            | into heavily-weathered     | 23000         | yes      |
| Layer | Strength | Depth | Weathering | Ultimate Bearing Capacity | Grouting | Notes |
|-------|----------|-------|------------|---------------------------|----------|-------|
| SZ02  | 1.2      | 28.0  | heavily weathered | 2.40m | 23000 | yes |
| SZ03  | 1.2      | 28.5  | heavily weathered | 2.40m | 23000 | yes |
| SZ04  | 1.2      | 31.0  | moderately weathered | 0.50m | 23000 | yes |
| SZ05  | 1.2      | 31.0  | moderately weathered | 0.50m | 23000 | yes |
| SZ06  | 1.2      | 31.0  | moderately weathered | 0.50m | 23000 | yes |
| SZ07  | 1.2      | 27.0  | heavily weathered | 2.40m | 23000 | no  |

Note: The pile shaft strength is C40; Quk signifies the value of the ultimate bearing capacity of a single pile; Grouting means grouting at pile side and end.

Purpose of test piles:
(1) To determine whether the characteristic value of the ultimate bearing capacity of a single pile was 23000 kN;
(2) To determine the ultimate lateral resistance of each soil layer after grouting and the ultimate end resistance of heavily and moderately weathered rocks to provide a basis for the design of pile foundation;
(3) To determine the grouting pressure at pile side and pile end.

2.3 The Stratum of Test Piles
In order to determine the stratum situation at test piles (SZ01-SZ07), 6 boreholes are arranged at the test pile location (SZ01-SZ06). The engineering geological profile is shown in Fig. 2. According to the site investigation report[11], the strata below the subsoil are as follows:

a. Silty clay (mixed with angular gravels) ③: brownish yellow to reddish brown, saturated, slightly dense to medium dense, with the angular gravels composed of schist, granite, and gneiss, mostly subangular, and containing coarse and gravel sands. The thickness of this stratum is 2.00 m to 13.40 m and the bottom elevation is −15.68 m to −6.62 m.

b. Silty clay ③1: brownish yellow, saturated, plastic to stiff plastic. This stratum occurs in the form of thin layer or lenticle, with a thickness of 0.80 m to 5.70 m.

c. Silty clay ④: brownish yellow to reddish brown, saturated, plastic to stiff plastic. This stratum is widely distributed in the site area. The thickness is 3.00 m to 12.50 m and the bottom elevation is −23.39 m to −13.15 m.

d. Fine to medium sand ④1: brownish yellow, saturated, medium dense to dense. This stratum occurs only in the form of thin layer or lenticle locally, with a thickness of 1.00 m to 2.00m.

e. Silt clay (mixed with angular gravels) ④2: brownish yellow to reddish brown, saturated, slightly dense to medium dense, angular gravels composed of schist, granite, and gneiss, subangular, and containing coarse and gravel sands. This stratum occurs in the form of a lenticle, with a thickness of 1.00 m to 2.30m.

f. Completely-weathered schist ⑤0: grayish green with the main mineral components of feldspar, quartz, and mica, the original rock structure destroyed, visible residual structure, easily softened by absorbing water, a thickness of 1.00 m to 6.50m and a bottom elevation of −26.89 m to 19.19 m.

g. Heavily-weathered schist ⑤1: grayish green with the main mineral components of feldspar, quartz and mica, the original rock structure destroyed mostly, the core mostly in earthy and fragmental form. The thickness is 1.00 m to 8.50m and the bottom elevation is −34.08 m to −20.37m.

h. Moderately-weathered schist ⑤2: grayish green, moderately-weathered with the main mineral components of feldspar, quartz, and mica; with lepidoblastic texture and schistose structure, relatively...
developed fissures, and the core mostly in fragmental and short columnar form. The maximum exposed thickness is 13.50 m and the bottom elevation is −41.39 m.

i. Completely-weathered gneissic granite ⑥: grayish yellow with the original rock structure destroyed and the mineral components changed significantly. The thickness is 1.90 m to 4.50 m and the bottom elevation is −22.52 m to −17.65 m.

j. Heavily-weathered gneissic granite ⑥: grayish brown with the main mineral components of feldspar, quartz, and mica, and with the original rock structure destroyed mostly. The thickness is 2.00 to 10.00 m and the bottom elevation is −33.25 m to −19.18 m.

k. Moderately-weathered gneissic granite ⑥: grayish brown, moderately-weathered with the main mineral components of feldspar, quartz, and mica; with medium to fine grained texture and gneissic structure, relatively developed fissures, and the core mostly in fragmental and short columnar form. The maximum exposed thickness is 6.50 m and the bottom elevation is −37.25 m.

Figure 2. Engineering geological profile of SZ01-SZ03 piles

3. Load Test and Optical Fiber Tests

3.1 Optical Fiber Layout
Considering that the optical fiber test has more advantages than the steel stress meter, and the test results are consistent with those obtained by the steel stress meter[12], we adopt optical fiber in the SZ01 and SZ05 piles as well as on the main reinforcement cage of test piles, and then sink the reinforcement cage into the boreholes for cast-in-place pile forming. The load test is carried out when the pile age reaches 28 days.

3.2 Test Instrument
The BOTDR monitoring equipment used in the test is the AQ8603 BOTDR fiber strain analyzer developed by Nippon Telegraph and Telephone Corporation (NTT). The optical fiber test of the two piles occurred from May 7, 2007 to May 17, 2007.

3.3 Fiber Strain Test of Pile Shaft
An optical fiber sensor is used to test the axial compressive strain distribution of pile shaft at each load level. The value measured before loading of the test piles by the BOTDR is used as the initial value, and the difference between the strain generated by loading and unloading at a certain level and the initial strain is taken as the strain generated under the action of the load.

3.3.1 Calculation Principle
The value measured by the test instrument is the axial compressive strain \( \varepsilon(Z) \) of the optical fiber. As the optical fiber is fixed in the pile concrete and the axial deformation of optical fiber is consistent with that of pile concrete under the action of load, therefore, the compressive strain of pile concrete is also \( \varepsilon(Z) \).

Then, the pile compressive stress \( \sigma(Z) \) is:

\[
\sigma(Z) = \varepsilon(Z) \cdot E_c
\]

(1)

where, \( E \) is the elasticity modulus of pile concrete.

The pile axial force \( Q(Z) \) is:

\[
Q(Z) = \sigma(Z) \cdot A
\]

(2)

where, \( A \) is the cross-sectional area of pile shaft.

The fundamental differential equation of pile load transfer is as follows:

\[
q_s(Z) = -\frac{1}{U} \frac{dQ(Z)}{dZ}
\]

(3)

where, \( q_s(Z) \) is the frictional resistance distributed at pile side

\( Q(Z) \) is the pile axial force

\( U \) is the pile shaft perimeter

The above equation can be simplified as:

\[
q_s(Z) = -\frac{1}{U} \frac{\Delta Q(Z)}{\Delta Z}
\]

(4)

where, \( \Delta Q(Z) \) is the variation of axial force between two cross sections of pile shaft in a soil layer

\( \Delta Z \) is the depth difference between two cross sections of pile shaft in the soil layer

By substituting Equations (1) and (2) into Equation (4), we get:

\[
q_s(Z) = -\frac{1}{U} \frac{\Delta Q(Z)}{\Delta Z} = -\frac{1}{U} \frac{\Delta \sigma \cdot A}{\Delta Z} = -\frac{A \cdot \Delta \varepsilon \cdot E}{U \Delta Z} = -\frac{A \cdot E \cdot \Delta \varepsilon}{U \Delta Z}
\]

(5)

where, \( \Delta \varepsilon \) is the variation of axial strain between two cross sections of pile shaft in a soil layer.

According to the results of optical fiber strain distribution obtained by the instrument, we can get all the test results as per Equations (1), (2) and (5).

3.3.2 Test Results

The test data under various loads is analyzed and calculated according to the above formulas to obtain the axial force distribution of SZ01 and SZ05 piles (see Figs. 3 and 4).
The lateral frictional resistance of SZ01 and SZ05 piles at each stratum under various loads is shown in Figs. 5 and 6.

The lateral resistance and end resistance of piles under various loads are shown in Tables 3 and 4.

Table 3. Lateral resistance of SZ01 pile under various loads (kPa)

| Pile top Load (kN) | ③ | ④ | ④_1 | ④_2 | ⑤_0 | Axial force at pile end (kN) |
|--------------------|----|----|------|------|-----|------------------------------|
| 4608               | 59.5 | 49.2 | 61.5 | 67.8 | 16.5 | /                            |
| 6912               | 75.9 | 66.8 | 99.9 | 108.6 | 31.9 | 6.6                          |
| 9216               | 86.3 | 86.7 | 143.1 | 150.5 | 62.1 | 21.3                         |
| 11520              | 107.6 | 81.9 | 176.2 | 202.2 | 71.7 | 15.8                         |
| 13824              | 127.1 | 80.1 | 187.1 | 272.2 | 111.3 | 40.5                         |
| 16128              | 150.5 | 86.1 | 211.6 | 303.1 | 140.1 | 20.1                         |
| 18432              | 168.5 | 123.7 | 247.3 | 318.8 | 166.6 | 210                          |
| 20736              | 184.4 | 147.6 | 256.2 | 396.6 | 193.7 | 28.9                         |
| 23040              | 196.8 | 179.6 | 292.5 | 418.5 | 219.1 | 298                          |

Table 4. Lateral resistance of SZ05 pile under various loads (kPa)

| Pile top Load (kN) | ③ | ④ | ④_2 | ⑤_0 | Axial force at pile end (kN) |
|--------------------|----|----|------|-----|------------------------------|
| 4608               | 61.3 | 92.3 | 37.0 | 14.0 | 9.4                          |
| 6912               | 79.0 | 144.2 | 60.4 | 27.8 | 28.9                         |
| 9216               | 95.9 | 189.5 | 82.0 | 34.2 | 49.2                         |
| 11520              | 104.3 | 211.4 | 109.6 | 46.3 | 53.5                         |
|                    |          |          |      |      | 267                          |
3.3 Load Test
Load tests are carried out on 7 piles according to the Technical Code for Building Pile Foundations (JGJ 94-94)\textsuperscript{[13]}, and the test results are shown in Table 5. It can be seen from Table 5 that the pile capacity can meet the design characteristic value of the ultimate bearing capacity of 23000 kN for a single pile when being embedded into the heavily-weathered and moderately-weathered layers, and that the pile deformation is very small under the load of 11520 kN.

Table 5. Load test results

| Pile no. | SZ01 | SZ02 | SZ03 | SZ04 | SZ05 | SZ06 | SZ07 |
|----------|------|------|------|------|------|------|------|
| Pile length (m) | 27.0 | 28.0 | 28.5 | 31.0 | 31.0 | 31.0 | 27.0 |
| Maximum test load(kN) | 23040 | 23040 | 23040 | 23040 | 23040 | 23040 | 23040 |
| Final settlement(mm) | 11.25 | 14.95 | 15.52 | 21.09 | 13.63 | 11.52 | 13.22 |
| $Q_{uk}$ (kN) | ≮23040 | ≮23040 | ≮23040 | ≮23040 | ≮23040 | ≮23040 | ≮23040 |
| $R$ (kN) | ≮11520 | ≮11520 | ≮11520 | ≮11520 | ≮11520 | ≮11520 | ≮11520 |
| Settlement under 11520kN(mm) | 4.21 | 4.70 | 5.50 | 6.89 | 4.83 | 5.01 | 4.19 |

Note: $Q_{uk}$ signifies the value of the ultimate bearing capacity of a single pile; $R$ depicts the characteristic value of bearing capacity of a single pile.

3.4 Analysis of Test Results
By analyzing the optical fiber test results, we can obtain the load sharing ratio of lateral resistance and end resistance under various loads, as shown in Tables 6 and 7.

Table 6. Load sharing of lateral resistance and end resistance of SZ01 pile under various loads

| Pile top load (kN) | Lateral resistance (kN) | Proportion of lateral resistance (%) | End resistance (kN) | Proportion of end resistance (%) |
|-------------------|------------------------|-------------------------------------|--------------------|----------------------------------|
| 4608              | 4608                   | 100                                 | /                  | /                                |
| 6912              | 6912                   | 100                                 | /                  | /                                |
| 9216              | 9116                   | 98.01                               | 100                | 1.09                             |
| 11520             | 11310                  | 98.18                               | 210                | 1.82                             |
| 13824             | 13526                  | 97.84                               | 298                | 2.16                             |
| 16128             | 15672                  | 97.17                               | 456                | 2.83                             |
| 18432             | 17856                  | 96.88                               | 576                | 3.12                             |
| 20736             | 19883                  | 95.89                               | 853                | 4.11                             |
| 23040             | 22019                  | 95.57                               | 1021               | 4.43                             |

It can be seen from Table 6 that the end resistance only accounts for 4.43% of the total load under the design characteristic value of the ultimate bearing capacity of 23040 kN, and 1.82% of the total load under the design characteristic value of the bearing capacity of 11520 kN for a single pile, indicating the great potential of pile end bearing capacity.

Table 7. Proportion of lateral resistance and end resistance of SZ05 pile under various loads

| Pile top load (kN) | Lateral resistance (kN) | Proportion of lateral resistance (%) | End resistance (kN) | Proportion of end resistance (%) |
|-------------------|------------------------|-------------------------------------|--------------------|----------------------------------|
| 4608              | 4608                   | 100                                 | /                  | /                                |
| 6912              | 6912                   | 100                                 | /                  | /                                |
| 9216              | 9216                   | 100                                 | /                  | /                                |
It can be seen from Table 7 that the end resistance only accounts for 9.92% of the total load under the design characteristic value of the ultimate bearing capacity of 23040 kN, and 2.32% of the total load under the design characteristic value of bearing capacity of 11520 kN for a single pile, indicating the great potential of pile end. From the analysis and load test curves mentioned above, it can be seen that after grouting of pile side and pile end, the bearing capacity of pile end has a certain potential when it reaches the value required by the design.

3.5 Application of Test Results
According to the test results, the final pile diameter was 1.2m, the effective pile length was not less than 27.0 m, the pile end was required to be embedded into the heavily-weathered layer for not less than 2.40 m, and the pile end and pile side were grouted. The designed number of piles was reduced from 274 to 244. The project was completed in November 2008 and has been in good running thus far.

4. Conclusions
According to the analysis of the load test and optical fiber test results, we can draw the following conclusions:

- Piles with a diameter of 1.2 m and the end embedded into heavily-weathered rock or moderately-weathered rock can meet the characteristic value of the ultimate bearing capacity of 23000 kN.
- The lateral resistance of soil layer is increased greatly by pile side grouting, especially silty clay (mixed with angular gravels) and fine to medium sand. Pile end grouting can eliminate the pile end sediments and improve the pile end resistance.
- Under the characteristic value of the ultimate bearing capacity of 23000 kN, the pile end bears 4.43% to 9.92% of the total load and the pile end bearing capacity has a certain potential.
- Optical fiber test is a good technique to determine the lateral and end resistances of piles under various loads.

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