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Compressive and Uplift Static Load Tests of Shaft and Base Grouted Concrete Bored Piles

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Tianjin, China

ABSTRACT

This paper provides an investigation of shaft and base grouted concrete pile behavior by conducting vertical compressive and uplift static load tests (SLTs) in Jinan, China. Three concrete piles were tested by compressive SLTs. Two of these piles were applied with shaft and base grouting, and base grouting technology respectively, and the third was applied without any grouting. Two uplift SLTs were carried out on one shaft and base grouted pile, and one pile without grouting. Traditional methods which include Load-settlement curvatures (L-s), Settlement-log time curvatures (s-lgt) and Time-log Load curvatures (t-lgQ) analysis were provided to check if the bored piles reached the design requirement. In addition, an interpretation of the test results from Double-tangent, DeBeer’s, and Chin’s methods (for compressive SLTs) and Mazurkiewicz’s method (for uplift SLTs) were provided for determining the ultimate pile capacity where piles experienced non-plunging failure. Results from the five SLTs program indicates that the Double-tangent and DeBeer's test results are close to each other whereas Chin's method overestimates the pile capacity; the base and shaft grouting pile and base grouting pile (compressive load) increases 9.82% and 2.89% of its capacity, respectively. Compared to the ultimate uplift SLTs, there is a 15.7% increment of pile capacity after using base and shaft grouting technology.

KEY WORDS: Shaft and Base Grouted Pile; Static Load Test (SLT); Pile Capacity.

INTRODUCTION

Piles are the long and slender structural components which transfer loading from upper structures (Tomlinson and Boorman, 2001). It is common for these piles to experience vertical compressive loading and sometimes these piles may also experience uplift loading, as in for example, the piles under a wind turbine. Pile foundation is popular because some situations occur where shallow foundations are not appropriate for resisting the loading transferred from structural elements (Samtani and Nowatzki, 2006). Such situations are: loads applied to foundation are very large; properties of some soil layers are not good enough; requirement needed as in the case where displacement must be kept small etc. (Knappett and Craig, 2012).

Pile foundation performs well in high-rise buildings due to its high value of bearing capacity. However, during the process of cast-in-situ construction, some soil deposits may remain at the base area after drilling the hole. These soil deposits are caused by collapse of soil layers and are very difficult to remove out of the drilled hole. This leads to a decrease of end resistance capacity of the pile and an increase of pile settlement. Because of these remaining soil deposits from the base of hole, it has been found that the capacity and settlement of some piles from a mansion are much lower than the designed requirement tested by static load tests in Taiyuan City, China (Shi, 2005). Furthermore, the drilling operation loosening the soil underneath the base of the bored hole also leads to excessive working load settlement.

Another problem associated with the bored pile is the utilization of admixtures like bentonite or polymeric slurry (slurry support) which is used for avoiding the collapse of soil layers into bored holes. The use of these materials may lead to capacity decrease of the pile shaft because these admixtures combine with soil and water, and then create a layer between soil and pile which consequently leads to a decrease in friction resistance of the pile. It is reported that this admixture layer or composite layer decreases 30% to 40% of the pile bearing capacity (Li et al., 2000).

Such limitations of cast in-situ concrete piles can be handled by base and shaft grouting techniques. The grouting equipment can be categorized into a flat jack system which consists of grout delivery pipes connected to a steel plate with rubber membrane and a sleeve-port system that consists of 2-4 U-tubes installed at the bottom of pile. This U-tube is covered by rubber and can be arranged in various configurations (Dapp et al., 2006).

Cement is a widely used grouting material. It is blended into various
ratios and then injected into the pile toe under high pressure transferred by a grouting tube. Through this technology, the grouting application will restore the original density of the base soil and reduce the settlement of the pile when loading transfers from upper structures (Tomlinson & Woodward, 2007). Moreover, as shown in Fig. 1, the grouted cement can also force out the soil-admixture layer which will lead to a decrease of shaft resistance, and consequently improve the friction between soil layers and pile surface.

Fig. 1 Cast-in-situ Concrete Pile Using Slurry Support Technology

Numerous studies have been conducted for determination of the effectiveness of this technology. Filed SLTs were conducted to compare the behaviors among one base grouted pile with two conventional slurry stabilized piles. This paper provided the load transfer characteristic and clarification of the mechanism of base grouted concrete pile. It also provided the correlation among cement consumption, the number of grouting stages and the volume of pile shaft (Ho, 2002).

The diameter of piles with grouting techniques ranges from 0.4m to approximately 2.5m. Tests of two piles were conducted at Paksey Bridge over the Padma (Ganges) River in western Bangladesh; the tested piles were 1.5m in diameter (Castelli and Wilkins, 2004). The construction of large diameter grouted piles with diameters of 2.4m were used in The Pinnacle, which is a 290m high skyscraper in London, England (Patel et al., 2015).

Besides an analytical method, the finite element method has been used for determining the bearing capacity for grouting treated piles. Recent tests and numerical simulation has shown that post-grouted concrete piles can double the ultimate capacity of a defected pile, and increase about 20% of a traditional pile’s capacity (Nguyen et al., 2012). Several case history projects with application of base grouting techniques were provided by Sinnreich and Simpson (2013), In their paper, Osterberg cell (O-cell) test method which can provide bi-directional axial compressive load, was utilized for determination of shaft and end bearing capacity; however, the results are inconclusive because some projects illustrate an increase of grouted pile capacity and some projects do not (Sinnreich & Simpson, 2013).

Pressure grouting piles or post-grouting piles had been successfully employed throughout the world for approximately 40 years (Mullins et al., 2000). Most of these grouting piles’ investigations concern base grouting; however, research into shaft grouting is very limited. Moreover, research has seldom considered the ultimate uplift bearing capacity of grouted bored piles. As for the analysis methodology, there is also limited case study evidence that refers to DeBeer’s, Chin’s methods etc. for SLTs interpretation. As Sinnreich and Simpson (2013) have pointed out, further research into the mechanics of grouting bored piles is needed as some results of ultimate bearing capacity between grouted and without grout piles have been paradoxical.

This paper provides five field SLTs for determining ultimate bearing capacity. Three compressive SLTs were conducted to one shaft and base grouted pile, one base grouted pile and one pile without grouting. Furthermore, two uplift SLTs were conducted to one base and shaft grouted pile and a pile without a grouting application. Besides the traditional SLTs interpretation (e.g. s-lgt), extrapolation of compressive and uplift SLTs are also provided in this paper. Finally, through analysis of the data from the test program, the capacities of each pile with different grouting methods are compared.

SITE CONDITION

The project is aims to build a 22 level office building with a height of 82.95m; the construction area is 50.8m×42.2m. This construction site is located in Jinan, China. The subsurface exploration was determined through laboratory and in-situ tests. The In-situ tests of standard penetration tests (SPT) and cone penetration tests and laboratory tests of consolidation tests, direct shear tests and triaxial tests were conducted based on the Chinese code of standard for soil tests method (GB/T 50123-2008,2008) and code for investigation of geotechnical engineering (GB 50021-2001, 2001) respectively. Based on the borehole logs, the simplified soil layers were then discovered and were summarized in Table 1 and 2.

Table 1 Simplified Soil Layers

<table>
<thead>
<tr>
<th>Soil Layers</th>
<th>Depth (m)</th>
<th>Average N Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miscellaneous Fill</td>
<td>2.61</td>
<td>5</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Gravel</td>
<td>3.5</td>
<td>21</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>3.5</td>
<td>21</td>
</tr>
<tr>
<td>Gravel</td>
<td>5.5</td>
<td>22</td>
</tr>
<tr>
<td>Residual Soil</td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>Weathered Diorite</td>
<td>4</td>
<td>41</td>
</tr>
<tr>
<td>Highly Weathered Diorite</td>
<td>1.7</td>
<td>43</td>
</tr>
<tr>
<td>Bearing Stratum</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

This project required underground carparks so the excavation construction started firstly with a depth of 9m. After the soil was removed, the cast-in-situ piles were cast and were surrounded by four layers. The soil layers are summarized in Table 2 with properties. The tested piles with P51, P121, P126 and P15, P16 were suffered from compressive and uplift forces, respectively. These five piles’ locations were approach with each other within 3 meters so the soil condition around the piles is similar. Note that layers of 1, 2 and 3 are Weathered Diorite, Highly Weathered Diorite and Bearing Stratum.

Table 2 Soil Layers around the Tested Piles

<table>
<thead>
<tr>
<th>Soil Layers</th>
<th>Depth (m)</th>
<th>(\gamma) (kN/m³)</th>
<th>C (kPa)</th>
<th>(\phi') (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>18</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>18.5</td>
<td>12</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>5.5</td>
<td>26</td>
<td>12</td>
<td>54</td>
</tr>
</tbody>
</table>

PILE DESCRIPTION

During construction process, P126 was cast using base and shaft grouting technology and P121 was cast using base grouting only. As for trial comparison and determination of the enhancement of this technology, P51 was cast without any grouting. These 3 piles were cast
using the same concrete and reinforcement with the same length of 19.5m.

For the pile which experienced uplift force, pile P15 and P16 were cast, with the only difference being that P15 was applied base and shaft grouting technology. Normally, uplift SLT could be conducted with P51, P121 and P126, but with consideration of loading influence by compressive SLT, this team determined to cast the other two piles for tests. As shown in Fig. 2, there were two grouting pipes used for base grouting, and one pipe was used for shaft grouting (P126, P15).

The traditional U-tube was selected for base grouting, but for the shaft grouting, a special device was designed as shown in Fig. 3. A steel tube with a diameter of 5mm was bent into a circular shape with a diameter of 800mm. This grouting tube was drilled with small holes with spacing of 150mm covered by a membrane which was used for avoiding the fine sand blocking the grouting after being welded to the shaft grouting pipe and reinforcement cage. Note that the base grouting was applied first.

![Fig. 2 Grouting Pipe of Concrete Pile](image)

The disadvantage of this device is that there is no guarantee of making this tube fit exactly into the drilled soil hole, which leads to the existing gap between soil layer and shaft grouting tube and consequently blocking some of the small holes for grouting after the concrete has hardened. This device therefore needs to be improved and further research conducted. Another issue is related to the location of the designed holes in this device as if this device is not arranged in a plane area, the pressure can be dissolved into lateral loading and, this would create shearing force as shown in Fig. 4. This issue was avoided, however, during the welding process.

As shown in Fig. 1, after base grouting, the pile may move up a little. If shaft grouting is upward, then it would push the pile back a little during grouting material. Another hypothetical device is provided here. The cross section of the shaft grouting tube can be improved as in Fig. 5; a small pipe is fitted into the hole which allows it to rotate. When the device was blocked by soil layers, the small pipe would change its position to the dished location and then it would move back to its original location with the help of a spring. This improved device can decrease the probability of shaft grouting failure, although the manufacturing process is complicated.

A description of the five tested piles is provided in Table 3; all piles were made of C50 concrete which characteristic cubic compressive strength of 50MPa (dimension of the cubic sample was 150mm × 150mm × 150mm). Reinforcement of test piles was HRB400 (Hot-Ribbed-Bar) with yield strength (f_y) of 360N/m. The reinforcement information is summarized in Table 4.
Table 3 Description of Test Piles

<table>
<thead>
<tr>
<th>Pile Label</th>
<th>Types of Tests</th>
<th>Length (m)</th>
<th>Dia. (m)</th>
<th>Concrete Strength</th>
<th>Compressive Strength (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P51</td>
<td>Compressive SLTs</td>
<td>19.5</td>
<td>800</td>
<td>C50</td>
<td>50</td>
</tr>
<tr>
<td>P121</td>
<td>Compressive SLTs</td>
<td>19.5</td>
<td>800</td>
<td>C50</td>
<td>50</td>
</tr>
<tr>
<td>P126</td>
<td>Compressive SLTs</td>
<td>19.5</td>
<td>800</td>
<td>C50</td>
<td>50</td>
</tr>
<tr>
<td>P15</td>
<td>Uplift SLTs</td>
<td>19.5</td>
<td>800</td>
<td>C50</td>
<td>50</td>
</tr>
<tr>
<td>P16</td>
<td>Uplift SLTs</td>
<td>19.5</td>
<td>800</td>
<td>C50</td>
<td>50</td>
</tr>
</tbody>
</table>

Two types of reaction piles were cast for conducting the compressive and uplift SLTs. The concrete strength of the compressive and uplift reaction piles were made of C35, in which characteristic cubic compressive strength was 35MPa with a depth of 19m and 16m respectively. The reinforcements were HPB300 (Hot-Plain-Bar) with yield strength ($f_y$) is 270N/m. These pile dimensions are the same with a cover of 50mm. The details are summarized in Tables 5 and 6. As shown in Fig. 6, the reaction piles which were welded to reaction beams were used for resisting the force created by hydraulic jacks.

Table 4 Reinforcement Information of Tested Piles

<table>
<thead>
<tr>
<th>Steel Bars</th>
<th>Dia. (mm)</th>
<th>Type</th>
<th>Spacing (mm)</th>
<th>$f_y$ (MPa)</th>
<th>Es (MPa)</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>14</td>
<td>HRB 400</td>
<td>N/A</td>
<td>360</td>
<td>2000000</td>
<td>0.3</td>
</tr>
<tr>
<td>Stirrups</td>
<td>Top 4m</td>
<td>8</td>
<td>HRB 400</td>
<td>100</td>
<td>360</td>
<td>200000</td>
</tr>
<tr>
<td>Stirrups</td>
<td>Other Part</td>
<td>8</td>
<td>HRB 400</td>
<td>200</td>
<td>360</td>
<td>200000</td>
</tr>
<tr>
<td>Stiffening Ring</td>
<td>14</td>
<td>HRB 400</td>
<td>2000</td>
<td>360</td>
<td>200000</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 5 Description of Reaction Piles

<table>
<thead>
<tr>
<th>Pile Label</th>
<th>Types of Tests</th>
<th>Length (m)</th>
<th>Dia. (m)</th>
<th>Concrete</th>
<th>Compressive Strength (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compressive Reaction Pile</td>
<td>19</td>
<td>600</td>
<td>C35</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>Uplift Reaction Pile</td>
<td>16</td>
<td>600</td>
<td>C35</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 6 Reinforcement Information of Reaction Piles

<table>
<thead>
<tr>
<th>Steel Bars</th>
<th>Dia. (mm)</th>
<th>Type</th>
<th>Spacing (mm)</th>
<th>$f_y$ (MPa)</th>
<th>Es (MPa)</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>12</td>
<td>HPB300</td>
<td>N/A</td>
<td>270</td>
<td>210000</td>
<td>0.3</td>
</tr>
<tr>
<td>Stirrups</td>
<td>Top 3m</td>
<td>8</td>
<td>HPB300</td>
<td>100</td>
<td>270</td>
<td>210000</td>
</tr>
<tr>
<td>Stirrups</td>
<td>Other Part</td>
<td>8</td>
<td>HPB300</td>
<td>200</td>
<td>270</td>
<td>210000</td>
</tr>
<tr>
<td>Stiffening Ring</td>
<td>12</td>
<td>HPB300</td>
<td>2000</td>
<td>270</td>
<td>210000</td>
<td>0.3</td>
</tr>
</tbody>
</table>

TEST SET-UP

**Compressive and Uplift Static Load Tests**

The SLTs were conducted after the concrete was sufficiently hardened. Four and two hydraulic jacks (QF630T-20) were used for providing loads during compressive and uplift SLTs respectively. For the compressive SLTs (P51, P121, P126), the loading started from 1800 kN, and increments of 900 kN were required for the next loading stage until the maximum load of 9000kN was applied. Later, the load was released with decrements of 1800 kN. For the uplift load tests (P15, P16), the loading started from 600 kN with increments of 300 kN. When the maximum load of 3000kN was reached, the load was released with decrements of 600 kN back to 0 kN.

According to Chinese codes GB50202-2002 and JGJ106-2004, for compressive SLTs, the settlement is recorded with intervals of 5, 15, 30, 45 to 60 minutes (1 hour later if required) and the followed loading applied when the variable quantity of the recorded movement is less than 0.1mm. The test will need to stop when recorded settlement is 1/5 of the settlement of followed loading. For the uplift static load tests, low speed maintenance tests were conducted. The applied load was maintained until the rate of axial movement did not exceed to 0.1mm. After each load was applied, recording the vertical movement of piles with intervals of 5, 10, 15 minutes, and 30 minutes was required if accumulated time exceeded 1 hour. The loading could be terminated in the case of the following conditions: 1) the applied loading is equal to the value of 0.9 times the ultimate strength of reinforcement, or 2) quintuple movement change of previous loading is discovered or 3: pile head movement is increased up to 100mm.

The steel reaction beams were connected to reaction piles as shown in Figs. 6. Four and two dial gauges were symmetrically set up to measure the compressive and uplift movements of pile heads (Fig. 7-8).
RESULTS AND DISCUSSION

Load-Settlement Curves of Compressive SLTs

After three compressive static load tests were conducted, the loads and corresponding settlement of P51, P121 and P126 were recorded. The load-settlement curve is provided in Fig. 9. It can be seen that after the maximum loading of 9000 kN was applied, the maximum settlements of pile heads were 11.68mm, 13.37mm and 11.74mm, respectively. The S-lgt and the S-lgQ curvatures of these 3 compressive loaded piles are provided in Figs. 10-15. Based on the code JGJ-106-2004, 4.4.2, clause 2: through S-lgt curve, the ultimate compressive bearing capacity can be found at the point that shows a downward trend. As shown in Fig. 10, the circled point shows an upward trend, and in Fig. 11, it shows the pile capacity of 2700 kN, which was actually caused by an error; in Fig. 12, there is no evident turning down point. The ultimate compressive bearing capacity of the pile cannot, therefore, be directly determine through S-lgt analysis.

Through S-lgQ curvatures, the ultimate compressive bearing capacity of piles were reluctantly determined to be about 6800 kN, 7100 kN and 8000 kN, respectively. The determination of pile capacity, however, needs more comprehensive analysis.

All these base grouted piles achieved the design settlement requirement, in which limited settlement should be less than 20-40mm. However, because there no plunging failure occurred, these data need to be interpreted.
Extrapolation of Non-failure Results of SLTs

The common method for plotting the failure criteria of drilled piles is the "double-tangent" method, as emphasized by AASHTO (2002) and FHWA (1992c) (Samtani & Nowatzki, 2006). In addition, the ultimate bearing capacity of pile can also be determined by DeBeer’s log-log method and Chin’s method. Through plotting data using logarithmic scales, the failure load and corresponding maximum vertical settlement can be determined (DeBeer, 1970). Chin (1971) assumed that the load-settlement relationship is hyperbolic and plots Δ/P versus load to determine the bearing capacity of pile. As provided in Eq. 1, the inverse slope of Δ/P results in the failure value is:

\[ Q_u = \frac{1}{C_1} \]  \hspace{1cm} (1)

Where: \( Q_u \) is the pile ultimate bearing capacity and \( C_1 \) is the slope of the plotted line.

When using the Double-tangent method, the bearing capacity of a pile can be directly obtained from the load-settlement curve (Fig. 9) by finding the intersection point of two tangent lines; the corresponding movement and load of this point are the ultimate bearing capacity and settlement. For Chin’s method, the coordinate unit should be changed as shown in Fig. 16.

Based on these methods, the bearing capacities as well as corresponding settlements of these three piles were obtained and are summarized in Table 7. It can be seen that all interpretation results illustrate that the pile capacity of base and shaft grouted pile is greater than the base grouted pile, and the capacity of piles with grouting technology was greater than the traditional treated pile.

### Table 7 Pile Capacity Based on Different Methods

<table>
<thead>
<tr>
<th>Pile Label</th>
<th>Double-tangent Load (kN)</th>
<th>Settlement (mm)</th>
<th>DeBeer's Load (kN)</th>
<th>Settlement (mm)</th>
<th>Chin's Load (kN)</th>
<th>Settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P51</td>
<td>7560</td>
<td>7.9</td>
<td>7600</td>
<td>7.9</td>
<td>10000</td>
<td>N/A</td>
</tr>
<tr>
<td>P121</td>
<td>7700</td>
<td>8.3</td>
<td>7900</td>
<td>8.3</td>
<td>10000</td>
<td>N/A</td>
</tr>
<tr>
<td>P126</td>
<td>8250</td>
<td>8.3</td>
<td>8300</td>
<td>8.2</td>
<td>11111</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Fig. 13 S-lgQ Curvature of P51

Fig. 14 S-lgQ Curvature of P121

Fig. 15 S-lgt Curvature P126

Fig. 16 Curvature of Chin’s Method
Load-Settlement Curves of Uplift SLTs

In order to check if the piles achieved the design requirement when the piles experienced uplift force, and to determine the pile capacity improvement of base and shaft grouting technique, two piles (P15 and P16) were selected for uplift static load tests. As shown in Fig. 17, when the maximum loading of 3000 kN was applied, the maximum vertical movement of P15 and P16 were 15.1 mm and 15.38 mm, respectively. It also illustrates that when loading from 0 kN to 3000 kN, all lines demonstrated linear. This illustrates that these two piles could resist more loading, and the maximum load settlement was not the ultimate load and settlement of the pile.

The S-lgt and S-lgQ curves are presented in Fig.18-21. As shown in Figure 18-19, it is difficult to determine the capacity through analyzing the S-lgt curves and the S-lgQ curves, and there are no plunging points as shown from Figs. 20-21. This also evidences that the pile achieves the designed load, but the maximum loading and corresponding settlement are not the ultimate bearing load and ultimate bearing settlement.
Extrapolation of Non-failure Uplift SLTs

The ultimate uplift bearing capacity of non-failure uplift SLTs can be determined by Modified Mazurkiewicz method (Thanadol K., 1998). The assumption is that the Nominate Settlement (Load/Settlement) value is equal to 0 when the loading is small and the settlement is very high; the dashed line would go through by y-axis which illustrates the uplift ultimate bearing capacity of the pile. As shown in Figs. 22 and 23, the ultimate uplift bearing capacity of P15 and P16 is 6299 kN and 5442 kN, respectively.

CONCLUSIONS

This paper provides the test set-up of static load tests, and various methodologies to determine the ultimate compressive and uplift bearing capacity when the data demonstrate non-plunging failure. It also shows that Double-tangent and DeBeer's methods’ results are close to each other whereas Chin's method overestimates the pile capacity.

A comparison of the ultimate compressive static load test results shows that the base and shaft grouting pile increases 9.82% of its capacity, and the base grouted pile increases 2.89% of its capacity. This suggests that the shaft resist dominated pile would increase its capacity better when applying shaft grouting than the pile with base grouting. Compared to the ultimate uplift static load tests, there is a 15.7% increment of pile capacity after using base and shaft grouting technology.

These tests were conducted without consideration of grouting materials. Further study should be initiated focusing on the influence of various materials, grouting pressure, as well as proportion of the grouting material to determine the best way to increase the pile capacity.

REFERENCES


