Influence of Grouting Pressure on Bearing Capacity of Pile Foundation Under the Sandy Soil

Junqi Du, Haiyan Li, Zhaofeng Li and Jian Zhang

ABSTRACT

The aim of the paper is to investigate the increase of bearing capacity of pile after grouting. In this paper, through the soil grouting reinforcement experiment and the numerical simulation of the bearing capacity of the pile, the increase of pile bearing capacity was investigated and compared with the standard method. Thus the relationship between grouting pressure, cohesion force and internal friction angle was obtained through grouting test. Grouting pressure has a great influence on cohesion force and a slight influence on internal friction angle. The lifting capacity of pile foundation obtained by numerical simulation is close to that of pile foundation obtained by formula. It is feasible to calculate the lifting range of bearing capacity of pile foundation by standard method.

INTRODUCTION

With the development of social economy, the road traffic is increasingly difficult to meet the increasing traffic volume. The road needs to be widened and the bearing capacity of the original pile foundation is insufficient.

Pile lateral drilling grouting is a kind of technical means to improve the bearing capacity of pile foundation by grouting. Compared with other methods to improve the bearing capacity of pile foundation, the grouting reinforcement of pile can save time and bring great economic benefits. Although the pile lateral drilling grouting reinforcement has its obvious advantages, there is also the problem that the increase of the bearing capacity of pile foundation can’t be accurately quantified. So the
development of pile grouting reinforcement renders a new method more accurate to calculate the increase of the bearing capacity of pile foundation.

At present, post-grouting has been studied by many scholars[1-5]. However, there are few researches on the bearing capacity of pile foundation strengthened by pile lateral drilling grouting. Grouting can improve the bearing capacity of pile foundation, but quantitative lifting of bearing capacity of pile foundation has not been solved. At present, the static load method is an accurate method to determine the bearing capacity of pile foundation[6-7]. However, the static load method is greatly affected by the environment and inconvenient. Thus, many scholars simulate the bearing capacity of pile foundation by numerical simulation[8-11]. FLAC3D is a 3D display finite-difference program developed by Itasca. It has been widely used in geotechnical engineering, mining engineering, tunnel engineering and railway engineering.

In this paper, through the soil grouting reinforcement experiment, the increase of soil internal friction angle and cohesion force were obtained, and the bearing capacity of pile foundation was simulated by the finite difference program FLAC3D through changing the value of friction angle $\phi$ and cohesion force $c$. Finally, the accuracy of the numerical simulation is verified by comparing with the standard method.

**EXPERIMENT**

**Test Device Design**

To investigate the increase of the internal friction angle and cohesion force of pile lateral soil, the grouting reinforcement system is designed mainly consisting of the container of soil and the grouting system.

The container is taken to be 300mm in diameter and 500mm high using 10mm thick High strength steel plate, and can be grouted through the bottom of the container. There are two removable lids on both sides of the container. Force is applied to the top of the container to prevent the slurry from backfill using a hydraulic jack when grouting. The grouting reinforcement system is shown in the Figure 1.

The grouting system mainly consists of two parts: grouting equipment, slurry preparation device. The grouting device adopts the gl70-90 grouting pump produced by Henan GengliCO., LTD. The grouting pressure of the grouting device is controllable, and the maximum of the grouting pressure can reach 8 MPa. The slurry preparation system is composed of slurry agitator and electronic scale with accuracy of 0.01Kg. The cement is stirred evenly using the slurry agitator and weighted accurately using the electronic scale.
Experimental Material

SOIL

Pressure grouting is a ground improvement or soil stabilization technique that involves injecting a fluid-like material under controlled pressure at strategic locations, via single or multiple ports, into soil or rock strata to improve their mechanical properties [12]. In this experiment, Sand and clay are selected for the experimental material from the Jingtai high-speed section, since these two types of soil are the most commonly seen. Consequently, it is representative to investigate these two types of soil. The main properties of these two types of soil are shown in Table I.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>density (kg/m³)</th>
<th>moisture content (%)</th>
<th>cohesive force (KPa)</th>
<th>internal friction angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>1940</td>
<td>13</td>
<td>15</td>
<td>34</td>
</tr>
<tr>
<td>clay</td>
<td>1740</td>
<td>13</td>
<td>63</td>
<td>25</td>
</tr>
</tbody>
</table>

GROUTING MATERIAL

The cement used is a locally available Portland cement. The grout was prepared by mixing a certain mass of cement powder and water using a blender at water/cement (w/c) ratio 1.

EXPERIMENT DESIGN

The grouting reinforcement experiment of sandy soil and clay was designed with grouting pressure as the independent variable. The grouting reinforcement tests were carried out when the grouting pressure was 0.5MPa, 1MPa, 1.5MPa and 2MPa respectively.
Experimental Results and Analysis

According to the design scheme of the grouting test, the experiment was carried out and direct shear test was carried out to investigate the variation law of the cohesion force and internal friction angle with the grouting pressure.

INTERNAL FRICTION ANGLE

The influences of grouting on the internal friction angle of clay and sand are shown in the Figure 2. It can be seen that the internal friction angle of clay increases more than that of sandy soil. It is mainly because that Clay particles have a rougher surface than sand. On the other hand, the compaction of slurry enhances the continuity and crisscross of soil. The slurry veins connect the soil mass as a whole. It can attribute the higher increase of internal friction angle when soil compactness increased after grouting.

![Figure 2. The change of the internal friction angle of the sand and clay.](image)

COHESION FORCE

The influences of grouting on the cohesion force of clay and sand are shown in the Figure 3. It can be seen that the Cohesion force of clay increases with a linear change while the Cohesion force of clay increases with a nonlinear change. The cohesion force of clay increases first increase and then decreases with the increase of the grouting pressure. It is mainly because that construction of the clay is damaged when the grouting pressure is higher than 0.5MPa for the reinforcement of clay, the most appropriate grouting pressure is 0.5MPa and for the reinforcement of sand when grouting pressure is 2MPa, the reinforcement effects more appropriate consequently, the bearing capacity of pile foundation is increased along with the increase of these two properties of soil.

When the grouting pressure is less than 2MPa, the cohesion force increases of sand with the increase of grouting pressure. The relationship between them is similar to the linear relationship. The increase of cohesion force of clay is enormous due to
the size effect. Thus, for the increase of cohesion force of clay, a reduction factor of 0.6 is considered.

![Figure 3. The cohesion force of sand and clay.](image)

NUMERICAL SIMULATION OF PILE BEARING CAPACITY

It is difficult to evaluate the bearing capacity of pile foundation after grouting. Thus, in this paper the 3D FD program FLAC$^{3D}$ is employed to investigate the increase of the bearing capacity of the pile foundation by establishing a single pile foundation model.

Modeling And Parameter Assignment

Considering the symmetry of the structure, half of the structure is taken for study. In this numerical simulation of pile bearing capacity, a simplified soil profile is used that the upper soil layer is sand with an embedment depth of 10m and the underling soil layer is clay with an embedment depth of 10m. The properties of these two types of soil before and after grouting are shown in the table II and table III as well as the model is shown in Figure 4. The pile is designed to be 1m in the diameter and 20m long. The properties of the pile foundation are set up that the elastic bulk modulus is 13.3e9 and the elastic shear modulus is 10.4e9 as well as the density of the pile is 2500kg/m$^3$. In addition, three interfaces between pile and soil are established according to the thickness of the soil. The interface can help us to simulate the frictional resistance and relative displacement between pile and soil. The attribute of contact surface is 0.8 times of that of nearby soil.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>poisson ratio</th>
<th>cohesion force</th>
<th>internal friction angle</th>
<th>density</th>
<th>soil thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>0.25</td>
<td>15KPa</td>
<td>34</td>
<td>1940kg/m$^3$</td>
<td>10m</td>
</tr>
<tr>
<td>clay</td>
<td>0.3</td>
<td>63KPa</td>
<td>25</td>
<td>1740kg/m$^3$</td>
<td>10m</td>
</tr>
</tbody>
</table>
Table III. THE PROPERTIES OF SAND AND CLAY AFTER GROUTING.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>poisson ratio</th>
<th>cohesion force</th>
<th>internal friction angle</th>
<th>density</th>
<th>soil thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>0.25</td>
<td>30KPa</td>
<td>37</td>
<td>1940kg/m³</td>
<td>10m</td>
</tr>
<tr>
<td>clay</td>
<td>0.3</td>
<td>80KPa</td>
<td>33</td>
<td>1740kg/m³</td>
<td>10m</td>
</tr>
</tbody>
</table>

Figure 4. The model of the numerical simulation.

Load Setting

In order to obtain the bearing capacity of pile foundation, the velocity of \(10^{-8}m/\)step is applied to the top of the pile through calculating with 710000 steps. Then the bearing capacity of pile before and after grouting is simulated numerically, thus the bearing capacity is obtained. The loading is applied in grade 9 and grade 11 corresponding with Static load test of pile foundation respectively. The first load applied is twice as much as the subsequent load. The loading design is shown in the Table V.

<table>
<thead>
<tr>
<th>Loading level</th>
<th>Before grouting</th>
<th>After grouting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (\circ)</td>
<td>260KN(\circ)</td>
<td>260KN(\circ)</td>
</tr>
<tr>
<td>2 (\circ)</td>
<td>390KN(\circ)</td>
<td>390KN(\circ)</td>
</tr>
<tr>
<td>3 (\circ)</td>
<td>520KN(\circ)</td>
<td>520KN(\circ)</td>
</tr>
<tr>
<td>4 (\circ)</td>
<td>650KN(\circ)</td>
<td>650KN(\circ)</td>
</tr>
<tr>
<td>5 (\circ)</td>
<td>780KN(\circ)</td>
<td>780KN(\circ)</td>
</tr>
<tr>
<td>6 (\circ)</td>
<td>910KN(\circ)</td>
<td>910KN(\circ)</td>
</tr>
<tr>
<td>7 (\circ)</td>
<td>1040KN(\circ)</td>
<td>1040KN(\circ)</td>
</tr>
<tr>
<td>8 (\circ)</td>
<td>1170KN(\circ)</td>
<td>1170KN(\circ)</td>
</tr>
<tr>
<td>9 (\circ)</td>
<td>1300KN(\circ)</td>
<td>1300KN(\circ)</td>
</tr>
<tr>
<td>10 (\circ)</td>
<td></td>
<td>1493KN(\circ)</td>
</tr>
<tr>
<td>11 (\circ)</td>
<td></td>
<td>1687KN(\circ)</td>
</tr>
</tbody>
</table>
Numerical Simulation Results and Analysis

Through numerical simulation, p-s curve and pile axial force curve as well as pile lateral friction curve were obtained. Thus, we can analyze the pile bearing capacity before and after grouting.

INFLUENCE OF GROUTING ON THE BEARING CAPACITY OF PILE

The bearing capacity of pile is shown in the Figure 5 in the case of before and after grouting. Before grouting, the pile was damaged when it was loaded to 1300KN, but after grouting, the pile foundation was damaged when it was loaded to 1687KN. The bearing capacity of the pile increases by 29.8%.

The reason for this phenomenon is that grouting changes the internal friction angle and cohesion force of soil. According to mohr-coulomb shear strength formula, it is found that the shear strength of soil is improved by changing the internal friction angle and cohesion force of soil. On the other hand, the compaction of the soil and the skeleton of the slurry by grouting increase the bearing capacity of the pile.

INFLUENCE OF GROUTING ON PILE SHAFT FORCE

Stress is monitored every two meters along the depth direction of pile body to obtain the axial force of pile body. The change trend of the pile shaft is shown in the Figure 6 in the case of before and after grouting. The axial force of pile decreases with the increase of pile depth. When the load reaches the maximum, the pile tip resistance value is still very small. This change is also the same as that of friction pile.
INFLUENCE OF GROUTING ON PILE LATERAL FRICTION RESISTANCE OF PILE

Figure 7 demonstrates the change of the pile lateral friction resistance of pile. In the sand layer, the maximum value of lateral friction increases from 75KN to 110KN after grouting. In the clay layer, the maximum value of lateral friction increases from 200KN to 275KN. The lateral friction resistance of pile increased from 1014KN to 1287KN, and the bearing capacity increased by 28.7%. This shows that the mechanical properties of soil are improved under the action of slurry cementation, compaction, splitting and "reinforcement"[13]. Consequently, Pile lateral friction resistance is increased.
Theoretical Calculation of Pile Bearing Capacity Based on Mohr-Coulomb Theorem

When the standard value of vertical ultimate bearing capacity of a single pile is determined according to the empirical relationship between the physical index of soil and the bearing capacity parameters, it is appropriate to estimate it according to the following formula[14]:

\[ Q_{UK} = Q_{SK} + Q_{PK} = u\Sigma q_{sik}l_i + q_{pk}A_q \]  \hspace{1cm} (1)

- \( q_{sik} \)—Standard value of ultimate lateral resistance of layer \( i \) soil at pile side
- \( q_{pk} \)—Standard value of ultimate resistance

According to mohr-coulomb theorem, the shear strength of soil is obtained by the internal friction Angle and cohesive force of soil. Considering that the friction force of pile foundation is related to the displacement between pile and soil, the displacement between pile and soil decreases along the depth of pile foundation. So the shear strength of pile soil interface should be multiplied by the reduction coefficient. Take 0.7 between 0 and 10 meters of pile depth and 0.5 between 10 and 20 meters of pile depth.

\[ \tau = \sigma \tan \phi + c \]  \hspace{1cm} (2)

\[ \xi = \frac{\mu}{1-\mu} \]  \hspace{1cm} (3)

\[ \tau = a(\xi \sigma \tan \phi + c) \]  \hspace{1cm} (4)

Where \( \tau \) is the shear strength, \( \sigma \) is the vertical stress, \( \phi \) is the internal friction angle, \( c \) is the cohesion force, \( \xi \) is lateral pressure coefficient, \( \mu \) is Poisson's ratio, \( a \) is reduction coefficient.

In order to compare with the results of numerical simulation, half of the pile is calculated. The bearing capacity of pile foundation is integrated along the direction of pile depth. The calculated friction force before grouting is 1597KN, and the friction resistance after grouting is 2029KN. Friction resistance increased by 27% which is close to the result of the numerical simulation.

The formula is used to calculate the bearing capacity of pile foundation, and compared with the results of numerical simulation, it is found that the formula can be applied to the calculation of bearing capacity of pile foundation

CONCLUSIONS

(1) The internal friction angle and cohesion force of soil can be significantly improved by grouting. In these two types properties, the increase of cohesive is
The increase of the internal friction angle of sand is feeble, which is contrary to that of clay.

(2) The bearing capacity of the pile increase by 29.8% in the case of grouting and non-grouting. The increased bearing capacity is mainly frictional resistance. In the sand layer, the maximum value of lateral friction increases from 75KN to 110KN after grouting. In the clay layer, the maximum value of lateral friction increases from 200KN to 275KN.

(3) Through the comparison between the formula method and numerical simulation, it is proved that the formula can be used to guide engineering and quantitatively increase pile bearing capacity.

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