Numerical study on the behavior of multi-propped deep foundation excavation

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Abstract

Many special supporting structures have arisen in deep foundation pits corresponding to different excavation methods, depths and geological conditions. In strata of soil-rock dualistic structure, design and construction experiences are far from adequate in double-row end-suspended piles. The supporting system of a deep foundation pit in Qingdao is taken as an engineering case to simulate the excavation process with the finite element software Plaxis. And then, comparative analyses are carried out between analytical results and real monitoring data. The results show that such double-row end-suspended piles has more stiffness and can effectively control the deformation of foundation pit and the displacement of the pile, which mainly concentrates in the depth range of soil strata. The conclusions can serve as a theoretical reference for the optimal design of similar support structures.

Keywords: Pile Foundation, Soil-Rock Dualistic Structure, Double-Row End-Suspended Piles, Deformation of Foundation Pit, Finite Element Method.

1. INTRODUCTION

With development of urban construction and the shortage of land resources, deep excavations of subways, civil air defences and high-rise building basements are more and more widespread in complex environment where buildings are thick and underground pipelines interconnected (Ding et al., 2015). Due to the above the influence of many factors, underground engineering for the rational development and utilization of deepexcavation technology in our country in recent decades, get a degree of development. However, a considerable number of problems in the development and construction design appeared in the various sectors, which may affect construction progress, inducing pit’s collapse, water gushing, sand gushing, threatening personal safety even directly made the excavation by halves (Guly et al., 2015; Yin et al., 2015; Hong et al., 2014). Therefore, many special and effective form of foundation pit supporting emerging in recent years and get a good application according to different situations, and how to select the reasonable foundation pits supporting form also become the key research problems of foundation pits supporting design. The theory and experience of the design and calculation of the foundation pit supporting structure of the pure soil is more mature, but it is still a difficult problem in the special “soil-rock” dualistic structure area (Liu et al., 2016; Hong et al., 2015). In the traditional supporting structure, the pile-anchor joints supportingsystem has the characteristics of strict control of soil deformation, good stability, economic and environmental protection. The double-row pile retaining structure has great lateral stiffness, which can effectively limit the deformation and displacement of supporting structure, construction technology is gradually perfect and developed in recent years, and it is widely used in deep foundation pit engineering because of a number of advantages of retaining structure (Cheng et al., 2017; Różylo et al., 2016; Zhang et al., 2016). There are many kinds of methods of foundation pit engineering, for example engineering experience, Model observation and theoretical analysis. Model observation method is rarely used because of the difficulty of implementation (Fenton et al., 2005). Among the methods, the Peck method is the most influential experience in all the estimation methods of surface subsidence, and the curve which can obtain the magnitude of subsidence and settlement distribution curve is dimensionless. The limit equilibrium method is the most commonly used method of engineering design, the key points are assumed to act on the retaining wall and soil structure, and the pressure reached the passive and active earth pressure, which is calculated using classical soil mechanics theory of force. On the basis of this, the mechanical structure of the statically indeterminate structure is simplified to statically determinate problem. This method is difficult to reflect the process of deep foundation pit excavation in the influence of various factors on the distribution of earth pressure on the supporting body, in another way this is approximation under certain conditions, and this method cannot
calculate the horizontal displacement of the supporting structure, and it does not reflect the continuity in the construction process of the stress of the supporting body, it is only a shallow pit or just support under the condition of great degree of approximation. Especially in soft soil deep foundation pit supporting structure, the calculation results have the actual discrepancy for deep foundation pit supporting more layers. The numerical method can reflect the various factors from time and space more comprehensive on supporting structure and surrounding soil stress and displacement, the direct solution of lateral wall displacement and surface settlement and deep displacement, but also on the excavation construction process simulation numerical method has broad application prospects. And the finite element method is the most useful method in numerical method. The calculation method of double-row piles of deep foundation pit supporting structure design is studied. Through the simulation of three-dimensional finite element to analyze the factors of double-row piles supporting structure and the deformation and stability of the system were discussed. In the paper, the deformation and instability were analyzed by using a combination bigFEM program Plaxis and combining with practical engineering cases. As for the internal support, the distance and rigidity of internal support were the two main influencing factors to be analyzed, with the aim of proposing appropriate parameters of the two factors. As for the rock-sock eted pile, numerical simulation was carried out on selection of the rocket length and bending rigidity of the piles. And by analyzing the variation of rocketed length and movement and bending moment of the piles, the design parameters could be proposed appropriately. At the same time, a monitoring program for it excavation is developed in accordance with the relevant specifications after analyzing the monitoring results and comparing hose with the theoretical results. Get some useful conclusions which are useful for design, construction and monitoring of similar engineering.

2. FOUNDATION PIT ENGINEERING EXAMPLE AND MODELING

2.1 Geological condition and foundation pit engineering

The geological condition of underground area is the oil-rock dualistic structure in Qingdao, and it may be the granite condition in a certain depth below the weathered and strongly weathered. In addition, the foundation pit is adjacent to the big mall, and there are a number of large buildings near the foundation pit. The more complicated geological conditions, the stricter requirements of the deformation of foundation pit. The typical support section of excavation is shown in the Figure 1.

![Figure 1. Typical support section of excavation](image)

The physico-mechanical parameters of soil layers are shown in table 1.
Table 1: Physico-mechanical parameters of soil layers

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Stratigraphic rock and soil</th>
<th>Thickness / m</th>
<th>Weight measure/ (KN·m⁻³)</th>
<th>Poisson's ratio</th>
<th>Cohesion/ kPa</th>
<th>Elastic Modulus/ MPa</th>
<th>Internal friction angle/ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fill the soil</td>
<td>2.5</td>
<td>16.0</td>
<td>0.40</td>
<td>10</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>coarse sand</td>
<td>3.5</td>
<td>16.0</td>
<td>0.40</td>
<td>0</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Silty clay</td>
<td>1.5</td>
<td>18.0</td>
<td>0.35</td>
<td>25</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Coarse sand</td>
<td>1.0</td>
<td>19.0</td>
<td>0.30</td>
<td>0</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>5</td>
<td>Strong weathered rock</td>
<td>4.0</td>
<td>23.0</td>
<td>0.29</td>
<td>0</td>
<td>46</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>Weathering rock</td>
<td>5.0</td>
<td>26.0</td>
<td>0.25</td>
<td>0</td>
<td>60</td>
<td>56</td>
</tr>
</tbody>
</table>

2.2 The design scheme of foundation pit supporting structure

The selection of the support excavation scheme not only satisfies the stability of the support system, but also requiring the support system to be economical and reasonable. The construction is convenient, and the most important thing is to ensure the safety and reliability of the surrounding buildings. Due to the geological condition which contains bedrock and hard rock, considering the existing technology and equipments, as well as the foundation pit engineering cost consideration and the limited depth of pile embedded in rock, and the factor of surrounding environment, construction and economy. Finally, the scheme of foundation pit supporting structure is determined, and the support unit with double-row end-suspended piles as shown in Figure 1.

The distance of double-row piles is 3m, the diameter of pile is 600mm, the strength grade of concrete is C25, and the design depth of embedded rock more than 1m. Rotary spray pile with high pressure jet grouting technique, the diameter is 800mm, and 200mm occlusion pile, the pile inserts into the strong weathered strata above 1m. The anchor parameters are shown in the table 2.

Table 2: Anchor parameters

<table>
<thead>
<tr>
<th>Anchor number</th>
<th>Rod type</th>
<th>Free section length/ m</th>
<th>Anchor fixed section length/ m</th>
<th>Design pull resistance/ KN</th>
<th>Pre-stressed/ KN</th>
<th>Horizontal inclination/ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG1</td>
<td>2$\times$32</td>
<td>15</td>
<td>8</td>
<td>587</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>MG2</td>
<td>2$\times$32</td>
<td>15</td>
<td>8</td>
<td>587</td>
<td>250</td>
<td>35</td>
</tr>
<tr>
<td>MG3</td>
<td>2$\times$32</td>
<td>15</td>
<td>8</td>
<td>587</td>
<td>150</td>
<td>35</td>
</tr>
<tr>
<td>MG4</td>
<td>3$\times$15.2</td>
<td>10</td>
<td>9</td>
<td>-</td>
<td>290</td>
<td>25</td>
</tr>
<tr>
<td>MG5</td>
<td>3$\times$15.2</td>
<td>10</td>
<td>7</td>
<td>-</td>
<td>290</td>
<td>25</td>
</tr>
<tr>
<td>MG6</td>
<td>1$\times$20</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25</td>
</tr>
</tbody>
</table>

2.3 The finite element modeling and simulation method

Plaxis is special finite element program software for the analysis of deformation and stability of geotechnical engineering. The software has friendly interface, simple modeling, automatic mesh generation, which can simulate the soil, including wall plate and beam structure, the contact surface, the elements and the soil anchor, geotextile, tunnel and pile foundation and so on. The strata can be regarded as homogeneous elastomeric condition, and the Mohr-Coulomb model is adopted.

2.3.1 The Mohr-Coulomb model theory
According to the test of sand, Coulomb the shear strength of soil $\tau_f$ is expressed as a function of the normal total stress on the sliding surface $\sigma$, the formula can be expressed in the following way

$$\tau_f = c\tan(\varphi)$$

(1)

And a more general expression for cohesive soils is presented

$$\tau_f = c\tan(\varphi) + c$$

(2)

where $c$ means the cohesion of soil and $\varphi$ is the internal friction angle of soil. The (1) and (2) can also be called Coulomb formula, and the formula (2) can be expressed that the formula satisfies the Mohr-Coulomb condition, it also can be said that if the shear stress of the object on the surface reach $\tau_f$, the point will yield.

According to the limit equilibrium condition of multiple stress circle, Mohr proposed the Mohr-Coulomb rule which is presented in the following way.

$$\frac{\sigma_1 + \sigma_3}{2}\sin(\varphi) - \frac{\sigma_1 - \sigma_3}{2} - c\cos(\varphi) = 0$$

(3)

### 2.3.2 The finite element model theory

In order to simplify the calculation, the following assumptions are made for the finite element model:

Assumption 1, the plane strain model is used in the foundation pit excavation, and the soil is modeled by Mohr-Coulomb elastic-plastic model.

Assumption 2, the retaining structure is regarded as the elastic stress state, and the supporting pile body is simulated by the elastic plate element without thickness

Assumption 3, the stress change caused by pile construction and excavation will not be considered.

And according to the assumption 1-3, without considering the influence of the initial stress, the displacement is 0 in model. Frozen soil unit, is the simulation of soil excavation. The geometric model is shown in Figure 2, two times the depth of foundation pit is 30m, which is the horizontal influence range, and the lower part is the middle-weathered granite, which is below the base of 15 m for the calculation range.

![Figure 2. Geometrical model and meshes of internal support](image-url)

In the finite element model, the bolt is simulated by the point to point anchor element and geo-grid. Among them, the geo-grid simulation of anchor, point to point simulation of the free section. The three-dimensional
stress state is complex around the anchor, the two-dimensional model cannot accurately simulate the interaction of the stress state and soil. But it can be simulated the stress distribution and the deformation and stability of structure in the overall level, bases on the assumption that the anchor section has no relative sliding condition. The cast-in-place pile is simulated by plate element, and the interaction between soil and structure is realized by interface element. Each simulation unit in the model is used to evaluate the different properties of the material.

The excavation of foundation pit is divided into 6 working conditions. Condition 1 is excavation of first and second layer of soil (3m), construction support pile and first anchor. Condition 2 is excavation which realizes to the level of the second anchor, the construction of second anchor. The condition 3 is the excavation of the soil which reach the lower bedrock surface, and the construction of the third anchor. Condition 4 is excavation of the fourth anchor. The condition 5 is the excavation of the soil which reach the Weathering interfaces, and the construction of the fifth anchor. Condition 6 is excavation of the sixth anchor. The depth of anchor of condition 1-6 are 3.0m, 7.0m, 8.5m, 10.5m, 12.5, 14m respectively.

3. RESULTS AND DISCUSSION

3.1 The analysis of pile Deformation

The displacement of supporting structure size not only plays an important role in the strength and stability of supporting structure, it also has a direct impact on the displacement of soil around the foundation pit. Control the displacement of supporting structure in a reasonable scope is an important guarantee for construction of the foundation pit and the surrounding environment safety. The displacement values of the piles at different depths are calculated at the different conditions, the results are shown in the figure 3.

![Figure 3. Displacements of pile under different conditions](image)

As we can see in the figure 3, during excavation, the displacement of the retaining structure increases with the increase of excavation depth. The maximum horizontal displacement of the pile is 20.89 mm, which appears at the top of the pile. According to the first level of safety control of foundation pit, the displacement value of the support structure is \(0.2\% \times H\), and the \(H\) is the depth of excavation. According to the depth of excavation, the max displacement is 28mm, so the max displacement is in the range of safety.

3.2 The ground settlements analysis of foundation pit

In the excavation process, not only to ensure the safety and stability of the foundation pit itself, but also to effectively control the deformation of the surrounding rock to protect the surrounding environment and buildings, and making them not to be affect. The relationship between depth of foundation pit and ground settlements is shown in the figure 4.
As we can see from the figure 4, the different excavation depth, ground settlements of excavation surface at different distances from the foundation pit has the corresponding relationship in the deformation of supporting system. And ground settlements have little change, during the upper excavation, and with the increase of the depth of excavation, the ground settlements become larger. The maximum value of ground settlements are located away from the excavation surface 5~7 m. Due to the restriction effect of the wall, the settlements are relatively small near the retaining pile. From 7m distance outside the pit, the influence of foundation pit began to weaken, and the deformation of surface began to decrease. In general, the ground settlements influence of excavation is in the range of two times foundation pit depth, and the influence is bigger in the range of the max depth of the foundation pit. In addition, the ground settlements tend to be stable far away from the excavation, indicating that the design parameters are reasonable.

3.3 The bending moments of foundation pit

According to the engineering experience, when the bending moment is measured, one side of the structure is pulled and the corresponding steel is pulled. The calculation of bending moments \( M \) can be calculated by the following formula

\[
M = \phi (\sigma_1 - \sigma_2) \times 10^{-5} = \frac{E_s}{E_c} \times \frac{I}{d} \times (\sigma_1 - \sigma_2) \times 10^{-5}
\]

(4)

Where \( \sigma_1 \) and \( \sigma_2 \) represent the reinforcement stress of excavation surface and back, \( E_c \) means elastic modulus of concrete structure, \( E_s \) represents elastic modulus of steel bar, and \( d \) means the center distance between the excavation face and the back-steelbar.

The calculation results of the bending moments of the retaining piles under different excavation conditions are shown in the figure 5. With the increase of excavation depth, the resistance of pile is also changing.

As we can see in the figure 5, the maximum value of bending moments appears in the condition 3, the maximum value is 102.98kN.m. The bending moments of pile are mainly affected by the excavation of foundation pit and the influence of anchor. Before the excavation of the bedrock depth, the bending moments of piles increases with the increase of excavation depth. When the excavation reaches the depth of rock, the bending moments of pile changes little with the increase of excavation depth. And bending moments of pile decrease after the influence of the anchor becomes appear. This is due to the role of anchor, which is equivalent to increase its elastic support.
3.4 The comparative analysis between real value and calculation value

In order to better illustrate the benefits of double-row end-suspended piles, the comparative analysis of displacement value and the ground settlements value are carried out in the following part. As we can know that with the increase of excavation depth, the horizontal displacement and vertical settlement of pile top increases gradually according to the above analysis, the calculated and measured horizontal displacement of soil is shown in figure 6, and the calculated and measured values of vertical settlement of pile top are shown in figure 7.
As we can see in the figure 6 and figure 7, the calculated values are greater than the measured values, because the finite element simulation is mainly based on the plane strain model, without considering the three-dimensional constraint in the real condition. And according to the figure 6 and figure 7, the results of finite element are closed to the measured results in the real condition. We can conclude that the finite element model of foundation pit is accurate, and it can simulate the real situation.

4. CONCLUSION

From the analysis of the above parts, we can draw the following conclusion.

(1) Combined with the design, construction and monitoring of the foundation pit engineering in Qingdao, the Plaxis software is used to calculate and analyze supporting system. The results show that double-row end-suspended piles are feasible in the geological condition of soil-rock dualistic structure, the overall stiffness of the supporting system can effectively control deformation displacement of foundation pit. It can be used for reference for the support design of foundation pit under similar geological conditions soil-rock dualistic structure, double-row end-suspended piles.

(2) The excavation of foundation pit and the stress of anchor are the main factors that affect the horizontal displacement of pile and the bending moments of pile; the maximum horizontal displacement of pile is located at the top of pile, and the displacement of pile bottom is the smallest.

(3) The finite element calculation model of foundation pit excavation adopts plane strain, but with the increase of excavation depth and width, excavation shape is more complex, it is necessary to adopt three-dimensional finite element calculation. In addition, the calculated results that adopt Mohr-Coulomb elastic-plastic model are close to the measured results, which can be used as the basis for design and calculation.

The main task of the application of computer vision technology to identify human motion from video images to obtain human posture, body movement, feature representation and recognition of human motion, so that the computer can understand people's behavior. The results of this study can be applied in more and more fields, such as advanced human-computer interaction, intelligent video surveillance, virtual reality, video retrieval, sports training, medical assistance and other fields. The research of human motion recognition based on vision involves many subject knowledge, which integrates the research achievements of many fields such as computer vision, pattern recognition, image processing, machine learning and so on. On the basis of summarizing and analyzing the main research achievements of human motion representation and recognition, this paper mainly studies how to represent and recognize the complex human motion in sports video. In this paper, we propose a new algorithm for the detection of human targets, the tracking of fast moving objects and the segmentation algorithm of human objects. By using the directional gradient histogram of the foreground image as the underlying feature, the self-similarity matrix of human body is established to represent and recognize human motion. Human body motion self-similarity matrix is used to represent human motion, which can eliminate the influence of camera motion in addition to the stability of viewpoint.

REFERENCES