Analysis of Influence of Deep Foundation Pit Dewatering Based on ABAQUS

YangXiu-zhu  
Central South University  
Changsha Hunan  
2050537464@qq.com

LvKai  
Central South University  
Changsha Hunan  
Lvkai2020@163.com

Lei Jin-shan  
Central South University  
Changsha Hunan  
5822673@qq.com

LiuJia  
Central South University  
Changsha Hunan  
1071233196@qq.com

ABSTRACT

The development of underground space domestic and abroad has always been plagued by groundwater problems, and safety accidents caused by deep foundation pits are common. Therefore by finite element simulation and in-situ methods, we studied the law of groundwater seepage and analysed the influence of dewatering construction for foundation pit based on the Shenzhen GangXia-North Transportation Hub Project. Then we obtained the seepage law of groundwater and the stress with deformation of the soil in the process of precipitation construction. It is found that within the scope of influence, the layered settlement of the soil meets the characteristics of “three-stage”; We compared among various numerical models under varying parameters and come up with the following conclusions:(1) The direction of groundwater varies with different precipitation speeds. When the speed is faster, vertical and downward seepage is dominate. As for lower speed, the seepage is mainly in the horizontal direction. This leads to discrepancies in the stress field of the soil, resulting in different deformations and settlements. (2) The effect of water stop curtain is significant. With the increase of curtain depth, the groundwater seepage velocity outside the foundation pit and ground settlement shows a decreasing trend. In addition, when the water stop curtain reaches a certain depth, the outside seepage can be completely blocked.

KEYWORDS: Deep foundation pit; Precipitation construction simulation; Effect of precipitation speed; Analysis of water curtain depth;

1 INTRODUCTION

At present, an growing number of foundation pits emerges along with the increased exploitation of underground space. In the process of underground space development, groundwater issues have always been a major potential risk of construction safety (Jiang Shao-xuan et al., 2018). On the one
hand, the groundwater softens the soil and weakens the strength of soil seriously, which significantly increase the probability of collapse and piping erosion. Thus, the excavation of foundation pit is seriously threatened (Zheng Gang et al., 2018); On the other hand, the groundwater level is usually reduced rapidly by means of well-point precipitation in actual construction. However, by this method, a large volume of water will be pumped out, which influences the surrounding area markedly, especially in densely constructed areas. At the same time, safety accidents occur frequently during the dewatering construction of foundation pits. Therefore, it is of great significance to conduct a deeper research of the seepage field, the fluid-solid coupling during the construction process and the influencing factors of soil deformation. Previously, many scholars have conducted in-depth research in these area. Luo Zu-jiang(2008) analysed the fluid-solid coupling of Quaternary sedimentary layer in Shanghai based on the problem of subway foundation pit dewatering by the numerical simulation. Yu Hong-liang(2002) further analysed the groundwater problems at different construction stages of foundation pit. Lu Jie-feng(2002) used finite difference software to simulate the groundwater seepage in the foundation pit and analysed the groundwater level under different working conditions. In terms of ground subsidence caused by groundwater, Ping Yang (2001), Luo Xiao-hui (2003), Feng Xiao-la (2005), Luo Zu-jiang (2006), Li Wen-guang (2008) have used numerical simulation software to analyse the seepage effect and surface deformation during the foundation pit dewatering process. Cheng Yun (2011) used orthogonal test to analyse the sensitivity of factors in affecting land subsidence. In short, the current calculations are mainly based on two-step calculation models, partial coupling models and fully coupled models (Gambolati G,1974. Lewis R W,1978.Chen Guo-xing,2009), but due to the uncertainties of the physical and mechanical properties of the soil, the groundwater seepage field is extremely complicated. The research on this issue is far from enough.

This paper is attached to the Shenzhen Gangxia North Comprehensive Transportation Hub Project. The in-situ test and numerical simulation are used to analyse the ground surface settlement caused by the precipitation construction. On the one hand, it aims to determine the characteristics of groundwater seepage, optimize the precipitation plan, adjust the layout planning of the precipitation wells, thus ensures the construction safety. Moreover, according to different influencing factors, such as precipitation speed, water curtain depth, the influence degree of this factor on the surface settlement outside the foundation pit is analysed, which is provides advantages to the targeted precipitation construction in the future.

2 ENGINEERING

2.1 Engineering Overview

Shenzhen Gangxia North Comprehensive Transportation Hub is constructed at the intersection of SZ Rail Transit Line 10,11,14 and the existing GX Station. It is, located at Shennan Avenue and Caitian Road. And it Situated in a densely populated area with a large group of high-rise. The total length of the major structure is 222.7m. The width of the standard section of the main retaining pit in the negative three-layer area is 39m. The width of the foundation pit on the east and west side is 50.5m, 50.8m respectively. It is a huge foundation pit that is rare domestic and abroad. The main structure of the foundation pit adopts 1000mm diaphragm wall and inner support enclosure structure.

2.2 Geological Condition

The geological survey shows that original landform of this hub is mainly the plain and valley. Due to the needs of urbanization construction, the site has been artificially reconstructed. And the current terrain is relatively artificial-filling, and the surface elevation is approximately 5.58m to 11.18m. According to the survey results of drilling, there are no fault structures found in the site. The strata is mainly constituted by the Quaternary Made Ground (Qml), the Quaternary Deposited and the Yanshan (γ53) granite. According to the geological exploration report, the surface water within the scope of the project site is less. The groundwater can be categorised into two types according to the type of medium in which it is stored: one is loose rock pore water, which is mainly exists in the Quaternary loose stratum, within the site. The recharge method of this type of groundwater is mainly precipitation and abundant water; the other type is bedrock fissure water, which mainly occurs in the intense weathering zone and middle weather zone, and the stable water level is generally higher than the aquifer. Surface replenishment is mainly due to atmospheric precipitation and pore diving.
3 ABAQUS FINITE ELEMENT ANALYSIS

Abaqus is a powerful engineering simulation software of finite element that solves problems ranging from simple linear analysis to complex nonlinear problems. Abaqus has a library of various types of materials that simulate the performance of typical engineering materials, including metals, reinforced concrete, and geological materials such as soil and rock. As one of the most advanced general-purpose nonlinear analysis software in the world, Abaqus continues to draw on the latest analytical theory and computer technology, and is the leader in the development of nonlinear finite element technology worldwide. At present, Abaqus software has been widely accepted by the world.

3.1 ABAQUS Model

For the sake of simplicity in calculation, finite element model applied in this report is based on the following basic assumptions: (1) Each soil layer is simplified as an homogeneous material with equal thickness, the soil is saturated, and the constitutive model is selected as the Mohr-Coulomb model; the structural materials such as the diaphragm wall and the internal support are regarded as linear elastic impervious materials. (2) The initial stress field of the soil is the static soil pressure stress field, the initial water pressure is the hydrostatic pressure, and the groundwater level is calculated according to the surface. (3) The stratigraphic boundary is regarded as horizontal, and the thickness of the soil layer is determined according to the average of the geological exploration report.

The size of actual pit plane is 51m (Y direction). Our calculation model size is 150m in the horizontal direction (Y direction), 100m in the longitudinal direction (X direction), and 80m in the vertical direction (Z direction). Perform displacement constraints on model boundaries at the beginning of the calculation. In addition, the bottom boundary is treated as an impervious boundary, the side boundary is considered as the boundary of the constant head, and the groundwater supply is adequate. The well and the diaphragm wall are arranged according to the construction drawing, as shown in Figure 1, in which the diaphragm wall is embedded in the impervious layer. In addition, the horizontal displacement is limited of the precipitation well boundary. Both the soil and the diaphragm wall are simulated by an eight-node three-degree-of-freedom pore pressure unit (C3D8RP), and contact constraints are set between the soil and the wall. The total number of units in the model is 129,064 and the total number of nodes is 85,400. The finite element model is shown in Figure 2. The calculation parameters of soil and structure are determined according to the geological survey report and the soil mechanics experiment shown in Table 1.

Fig.1 Precipitation well layout                                      Fig.2 Calculation model diagram
Table 1: Material Mechanical Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>E (MPa)</th>
<th>Poisson Ratio</th>
<th>γ (kN/m³)</th>
<th>C (KPa)</th>
<th>Friction Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime fill</td>
<td>4</td>
<td>0.3</td>
<td>19.1</td>
<td>12</td>
<td>35</td>
</tr>
<tr>
<td>Clay soil</td>
<td>25</td>
<td>0.3</td>
<td>18</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>Fully weathered granite</td>
<td>30</td>
<td>0.28</td>
<td>18.3</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td>Strongly weathered granite</td>
<td>60</td>
<td>0.25</td>
<td>18.7</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>Medium weathered granite</td>
<td>80</td>
<td>0.2</td>
<td>25.7</td>
<td>27</td>
<td>29</td>
</tr>
</tbody>
</table>

In order to simulate the precipitation process on the construction site, we divided the calculation analysis into 11 analysis steps. Step 1: Establish the initial geostress field. Step 2: Simulate the water level in the precipitation well to drop by 2.8m. The analysis steps 3 to 11 are all precipitation simulations, each of which is 2.8m deep, that is, a total of ten precipitation analysis steps reduce the water level in the well by 28m. The precipitation simulation is realized by defining the model’s free-drainage flow, under which the pore water is only allowed to seep out from the boundary area of the precipitation well. The relationship between the water seepage speed and the pore pressure is followed:

\[ v_n = k_w u_w, \quad u_w > 0 \]  \hspace{2cm} (1)
\[ v_n = 0, \quad u_w \leq 0 \]  \hspace{2cm} (2)

3.2 Calculation Result

Under the above geological and hydrological conditions, the foundation pit precipitation simulation is carried out, and the maximum settlement of the ground surface outside is 0.003m, the maximum settlement distance is 41.42m from the diaphragm wall, and the water level drop height is 0.2m; the maximum surface settlement in the foundation pit is 0.1m, the maximum settlement is around the precipitation well, the water level drops to 28m. Then we chose a typical Y-Z section in the centre of the model as the research object. And the calculation results of surface settlement on this section are shown in Figure 3.

![Fig.3 Surface Settlement Curve of Soil](image-url)
Through the simulation calculation results, it can be seen that the pressure in the foundation pit changes due to the precipitation, and the water level in the vicinity of the precipitation well decreases significantly. The soil enters the unsaturated state and exhibits negative pore pressure, and the surface settlement is obvious. On the other hand, the seepage of the groundwater outside the foundation pit is blocked because of the diaphragm wall, so that the influence of the precipitation construction on the surrounding water level and the surface settlement outside the foundation pit is small. In order to figure out the vertical strain characteristics of the soil after precipitation construction, we extracted the strain of each element of the soil around the precipitation well. And we equivalent it to the settlement of a unit of thick soil for observation, which are shown in Figure 4. From this figure, we can see that the soil in each layer has different settlement after precipitation, and the settlement value of the fully weathered granite in the 25m-35m section below the surface is larger.

![Figure 4: Soil Settlement Curve](image)

It can be seen from the above figure that the soil settlement caused by the precipitation of confined aquifers satisfies the "three-stage" (Zeng Chao-feng, 2014) stratified sedimentation law, that is, the settlement law of the overburden soil (buried depth 0-30m) is “upper and lower”, while in the deep soil (under 30m depth), the settlement law is “deeper and lower”. This is because in the overlying soil, the water level is deeper, the pore pressure of the soil does not change substantially, and additional tensile stress may be generated near the surface of the soil. While in the deep soil, the soil porosity is lower, the soil permeability coefficient is smaller, and it can be considered as an impermeable layer, so the additional stress of the soil is also small. For further analysis, we show the soil void ratio curve in Figure 5.

![Figure 5: Void Ratio Curve](image)
It can be seen from the figure that the drop of the groundwater level causes a certain compression of each soil layer, and the void ratio is reduced. In addition, the porosity ratio of the soil layer with larger settlement is also significantly larger, indicating that the soil particle redistribution is important reasons for settlement. In short, the groundwater level drops, the soil enters the unsaturated state, and the effective stress of the soil increases. Under the action of this force, on the one hand, the soil particles themselves are deformed and compressed, on the other hand, the soil particles are displaced, the void ratio gets smaller, the soil skeleton shrinks, and the soil is reconsolidated.

3.3 Settlement Mechanism

According to the theory of effective stress of Terzaghi, the total stress of saturated soil is equal to the sum of effective stress and pore water pressure acting on the soil skeleton. In the above analysis, there is no surface loading, so the total stress in the horizontal section at any depth of the soil should be equal to the sum of the water column weight and the soil column weight on the section:

$$\sigma_z = \gamma_w h + \gamma_w h$$

Therefore, its effective stress is:

$$\sigma = \sigma_z - u = (\gamma_{sat} - \gamma_w) h = \gamma' h$$

(2)

Considering the effect of the seepage force, assuming a section of the surface of the soil with \(h\), and the head difference between the two sections is \(\Delta h\), then the hydraulic gradient \(i = \frac{2h}{\Delta h}\), so the effective stress of the soil is:

$$\sigma' = \gamma' h + \gamma_{sat} h - \gamma_w (h - \Delta h) = (\gamma' + i\gamma_w) h$$

(3)

After the precipitation, the pore water pressure in the soil completely dissipates, and the effective stress of the soil becomes the weight of the soil.

It can be seen from the above analysis that the seepage force generated by groundwater seepage and the dissipation of pore water pressure after precipitation is the main cause of soil deformation. So, the effect of pore water pressure dissipation on soil settlement is only related to the depth of precipitation. The greater the water level decline, the greater the increase of soil effective stress, and the greater the settlement value. The groundwater penetration force is related to the water level decline rate and the head loss. In the groundwater seepage, the head loss is mainly related to the soil porosity and the soil skeleton roughness. Therefore, the surface subsidence caused by the foundation pit precipitation is mainly related to the depth of the groundwater level, the rate of water level decline, and the porosity and grain roughness of the soil.

4 ANALYSIS OF INFLUENCING FACTORS

4.1 Precipitation Speed

In the actual construction process, the properties of the soil itself are generally unchangeable, and according to the construction requirements, the depth of the water level is also certain. So, in order to control the surface settlement, we can achieve the speed by controlling the precipitation. Therefore, according to the above calculation model, we changed the precipitation rate of the foundation pit and calculated the deformation of the soil under the condition that the water level drops by 1m, 2m, 3m and 4m per day. According to the results, we found that the groundwater seepage direction is different under different precipitation speeds. When the water flow decreases by 1m every day, the water flow direction flows to the precipitation well in the horizontal direction. When the water drops by 4m every day, the water flow mainly flows vertically downward. The main reason is that when the precipitation speed is fast, the pore water pressure is deep in the soil, and the water seepage speed is faster in the precipitation well. Therefore, a large negative pressure is formed in the depth of the soil, so that the groundwater of the upper layer is concentrated downward. We show the ground settlement of the soil under different precipitation speeds in Figure 6, and the maximum settlement of the surface is shown in Figure 7.
It can be seen from Fig. 6 that under different precipitation speeds, the ground settlement law of the soil is basically the same, and the maximum settlement occurs around the precipitation well. It can be seen from Fig. 7 that the maximum settlement and precipitation velocity of the surface are not completely linear. When the precipitation velocity is relatively small, the rate of change has little effect on the surface settlement. This is because when the precipitation speed is small, the precipitation will have a higher internal water level, and the groundwater seepage path will be dominated by the horizontal direction. Therefore, the horizontal penetrating force of the soil is equivalent to two-way compression, so the settlement is small; When it is faster, the water level in the well is lower, the groundwater seepage is dominated by the vertical path, the direction of the penetrating force is the same as the direction of gravity, the effective stress of the soil increases, and the horizontal penetrating force decreases, thus causing a large settlement.
4.2 The Embedded Depth of Water Curtain

In the construction of the Gangxia North Project in Shenzhen, the water-stop curtain is combined with the diaphragm wall. Therefore, in the above simulation calculation, the diaphragm wall can completely block the seepage of water. The groundwater seepage in the soil was shown in Figure 8.

![Fig.8 Seepage velocity and direction of groundwater in soil](image)

In the above figure, the water curtain is 7m deeper than the precipitation well. It can be seen from the calculation results that the water curtain has obvious barrier effect on the groundwater, so that the flow velocity outside the foundation pit is much smaller than that inside the foundation pit, which greatly reduces the impact on the surrounding environment. Under this condition, we obtained a settlement of 0.02m outside the foundation pit. Therefore, based on the ground settlement outside the foundation pit, we calculated the working conditions of different water curtain embedding depths, and we obtained the result shown in Figure 9.

![Fig.9 Maximum surface settlement under different depths of water curtain embedding](image)

Through the analysis of the calculation results, we can know that within a certain range, the surface settlement has a linear relationship with the depth of the water curtain; when the depth reaches a certain depth, the surface settlement remains basically stable. The reason may be that the water is stopped at this depth. The curtain can completely block the seepage of groundwater inside and outside the foundation pit, so that the cause of soil settlement outside the foundation pit is no longer caused by
seepage, but the ground stress field caused by the deformation of the soil in the foundation pit, and the horizontal stress change of the soil causes vertical deformation is deformed, so its settlement value is no longer affected by the curtain depth.

5 FIELD EXPERIMENT

In order to obtain more realistic and accurate data to analyze the groundwater seepage principle, we conducted single well pumping and well group pumping test in the northwest work area of Gangxia Shenzhen according to the specification requirements and the on-site precipitation well layout plan. The single well pumping test was carried out in three drawdowns, namely, deep drawdown (20m), medium-deep drawdown (12m) and small drawdown (6m); the well group pumping test only had a small drawdown. The specific test process is shown in Table 2. XJS-44, XJS-53, XJS-56 and XJS-59 were selected for single well pumping. XJS-7, XJS-10 and XJS-11 were selected for well group pumping, and an observation well GJ-1 was drilled separately. The layout is shown in Figures 10 and 11.

![Fig.10 Single well pumping test well layout](image1)

![Fig.11 Well Group Pumping Test Well Layout](image2)

<table>
<thead>
<tr>
<th>Well</th>
<th>Draw Down</th>
<th>Time/h</th>
<th>Stable Time/h</th>
<th>Recovery Time/h</th>
<th>Water Outflow (L/S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XJS-44</td>
<td>6m</td>
<td>0.5</td>
<td>24</td>
<td>12</td>
<td>0.333</td>
</tr>
<tr>
<td></td>
<td>12m</td>
<td>1</td>
<td>24</td>
<td>12</td>
<td>0.484</td>
</tr>
<tr>
<td></td>
<td>20m</td>
<td>3</td>
<td>24</td>
<td>12</td>
<td>0.588</td>
</tr>
<tr>
<td>HJS-7, 10, 11</td>
<td>6m</td>
<td>0.5</td>
<td>120</td>
<td>36</td>
<td>0.301</td>
</tr>
</tbody>
</table>

According to the above test procedure, we come up with the relationship between pumping flow (Q) and depth reduction (S). Then we plot the Q-s curve characteristics to reflect the corresponding groundwater type as shown in Figure 12.

![Fig.12 Q-s Curves](image3)
Through the field test data, we calculated the soil permeability coefficient by using the Dyumanic formula and the Girhard formula, and the average soil permeability coefficient of the test section was 0.81 m/d, which was 1.07 m/d compared with the geological exploration data. The decrease is 24.3%. The reason is that the pile foundation and the construction of the diaphragm wall make the soil porosity lower and the soil more compact.

6 CONCLUSION

Based on the Shenzhen Gangxia North Comprehensive Transportation Hub Project, this paper uses ABAQUS software to establish a three-dimensional calculation model from the influence of foundation pit dewatering construction on the surrounding environment, and analyzes the influence of precipitation speed and water curtain depth on precipitation construction. Soil settlement and deformation law under different working conditions. The following conclusions were obtained:

(1) The influence of foundation pit dewatering construction was simulated by using the free effusion section boundary conditions of ABAQUS software. The analysis believes that this method can meet the calculation requirements of actual construction, and it is an effective finite element calculation method; the stratified settlement of soil satisfies the distribution characteristics of “three-stage”, and the surface settlement of soil is larger.

(2) The construction effects under different precipitation speeds were calculated by finite element analysis. The calculation results show that the difference of precipitation speed makes the change of soil effective stress greatly different during the construction process, so the impact on surface settlement is significant.

(3) The analysis simulates the role of the water curtain in the process of groundwater seepage. The results show that the water curtain can effectively block the groundwater seepage in a certain depth and reduce the impact of precipitation in the foundation pit on the surrounding environment. Therefore, in the actual construction process, we must pay attention to the construction of the water curtain, minimize the impact of the construction process on the water system at the construction site, and ensure the safety of the surrounding structures.

(4) Single well and well group pumping tests were carried out on site. Through experiments, we have come to the conclusion that the soil permeability coefficient is different from that during the geological survey because it is caused by on-site construction. Therefore, in the future calculations, we should consider the influence of site factors on groundwater seepage and soil stress. Do more accurate calculations and simulations.

REFERENCES


Zeng Chao-feng(2014).Study on deformation mechanism, behavior and control strategy of excavation and ground under dewatering(D).