

Proportion Analysis of Ground Settlement Caused by Excavation and Dewatering of A Deep Excavation in Sand Area

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Abstract Ground settlement caused by combined influence of excavation and dewatering in sand area is discussed in this paper. The soil seepage-stress interaction model in a deep excavation is established based on the modified Mohr–Coulomb model using finite element theory, in order to analyze seepage field and ground settlement surrounding the deep excavation caused by well dewatering and soil excavation. Ground settlement caused by excavation and dewatering individually are obtained from the numerical investigation. A case history in northeastern China is adopted in this study, and the results show that, impact of ground settlement caused by excavation and dewatering is about three times the excavation depth (H). The maximum settlement point of monitoring sections appears at a distance of 22 m from the deep excavation, about 0.82–0.96 H . The ground settlement caused by soil excavation is dominant from 10 to 20 m away from the deep excavation, while the ground settlement beyond 25 m from the excavation is mainly caused by dewatering. Settlement caused by dewatering is kind of irreversible settlement, so the ground settlement of a deep excavation caused by well dewatering can not be ignored during design and construction of excavation engineering.

Keywords Ground settlement · Dewatering · Foundation excavation · Seepage-stress interaction · Sand area

Introduction

With the advancement of urban construction, high-rise buildings and underground rail transportation are becoming more and more common in urban engineering. The foundation pit engineering, especially the deep and large foundation pit engineering becomes more and more universal in city projects. In shallow groundwater area, the underground aquifers will be exposed by foundation pit excavation, causing the foundation pit seepage failure. So it is extremely important to conduct dewatering before the pit excavation. In addition, seepage pressure caused by excavation dewatering will cause compression of the soils surrounding the excavation pit, and ground settlement caused by this phenomenon is also unignorable [1–4]. Soils will move into the excavation pit during the unloading process which will cause ground settlement in pit surrounding areas. Settlement over the critical value will extremely threaten the safety of buildings and roads. Thus, mechanical mechanism of ground settlement caused by foundation excavation is widely studied by scholars in China and rest of the world. Shi chenghua [5] proposed the calculation method of ground settlement caused by excavation and dewatering based on stochastic media theory, seepage theory and soil consolidation theory, the formula of final ground settlement distribution caused by excavation and dewatering was obtained using the principle of superposition. According to the principle of effective stress and seepage theory, Cao and Zhang [6] obtained two basic reasons of ground settlement, lateral deformation and changing of effective stress. Three-dimensional fluid–solid coupling model considering the transient dewatering of the well was established by Zheng [7] using the finite element software ABAQUS, the deformation mechanism of retaining caused by dewatering before the excavation was

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studied. It was pointed out that the first horizontal support installation can effectively reduce the deformation caused by excavation. Soil–water coupling model was established by Zujang et al. [8]. Combining the groundwater seepage field and soil stress field, based on the Biot's consolidation theory, considering the dynamic change of soil permeability, the groundwater level and settlement were obtained. Jian [9] obtained the relationship between the seepage field and the seepage induced settlement in different dewatering conditions based on the Mohr–Coulomb yield criterion and the saturated–unsaturated soil seepage theory.

Soil seepage–stress full coupling model was established in this paper, using MIDAS-GTS finite element software. Modified Mohr–Coulomb model was adopted to simulate the ground settlement caused by excavation and dewatering. The settlement rules of surrounding soils were studied based on the monitoring data obtained during a deep foundation pit excavation.

Introduction of the Project

The studied subway station is located in Hunhe river forest park and it is set at the north–south direction, with the city two-ring ramp in the north, Evergreen Street in the west, Hunhe river forest park in the east and Hunhe river in the south. It is a rectangular shape subway station of three storeys and spans, inland platform with reinforced concrete framed structure. The maximum width of the station is 25.3 m, and the main structure is 148.4 m in length (Fig. 1). The station was constructed by open cut method and the excavation depth is mainly range from 23.3 to 26.6 m. The whole construction period is 18 month.

Bored grouting piles were used as the supporting structures according to the hydrogeological, engineering geological conditions and the surrounding environmental factors. Parameters of the piles are as follows, the length of the pile is $L = 33$ m, the diameter is $\varphi = 1000$ mm, center



Fig. 1 Diagram of the study excavation pit

to centre distance is $d = 1400$ mm. There are four-layer inner support inside the foundation pit, the diameter of the first and second inner support is $\varphi = 609$ mm, the thickness of the steel pipe support is 12, 16 mm respectively; the diameter of the third and the fourth inner support is $\varphi = 800$ mm, the thickness of steel pipe is 16, 12 mm respectively (Fig. 2). The inverse corner strut support, which is vertical to the horizontal inner support, with a diameter and thickness of 609 and 12 mm, respectively. They are set under the cap beam from top to the bottom of the excavation pit at the position of 7,6.5,4.5 and 4.5 m respectively. There are steel support and diagonal bracing in the planar direction of the excavation pit (Fig. 3). Steel mesh spraying concrete of 100 mm thickness is used to hang between the bracing piles in order to smooth the space between two piles. 39 pumping wells (diameter $\varphi = 429$ mm) are put around the excavation pit every 10 m, pipe well dewatering method is adopted to decrease the groundwater level because the high permeability (82 m/d) of aquifers in construction site. The wells keep pumping for 10 days until the groundwater level decrease to the bottom of the excavation pit. The maximum groundwater difference between outer excavation pit and inner excavation pit is 19 m. The profile of supporting system and layer distribution are showed in Fig. 2.

Monitoring Data of Ground Settlement and Dewatering around the Foundation Pit

Analysis of Seepage Field Around Foundation Pit

The foundation pit is located in the middle of the alluvial fan, with continuous distribution of sedimentary strata, mainly of coarse particles and only local sections overlying clay lens body. Groundwater in study area is exposed to pebble and sand gravel layer, and the scope of investigation is mainly within pore phreatic water depth. The stable groundwater depth is about 6.60–12.30 m and the thickness of aquifer is 28.0 m. The bottom depth and the maximum depth of the foundation pit is 23.3 and 26.6 m respectively, the maximum groundwater head difference of outer and inner excavation is about 19 m. Pumping wells are arranged outside the excavation pit due to the large excavation scope of the foundation pit, observation wells are set around the pit and numbered from SW1 to SW10 (Fig. 3). The contour map of the groundwater level before and after the excavation is shown in Fig. 4.

The foundation pit dewatering changes the seepage fields of excavation pit (Fig. 4a). Initial groundwater level is from 34.63 to 34.92 m in Fig. 4a, the direction of groundwater flow is from the southeast to the northwest because the excavation pit is next to Hunhe river and it will

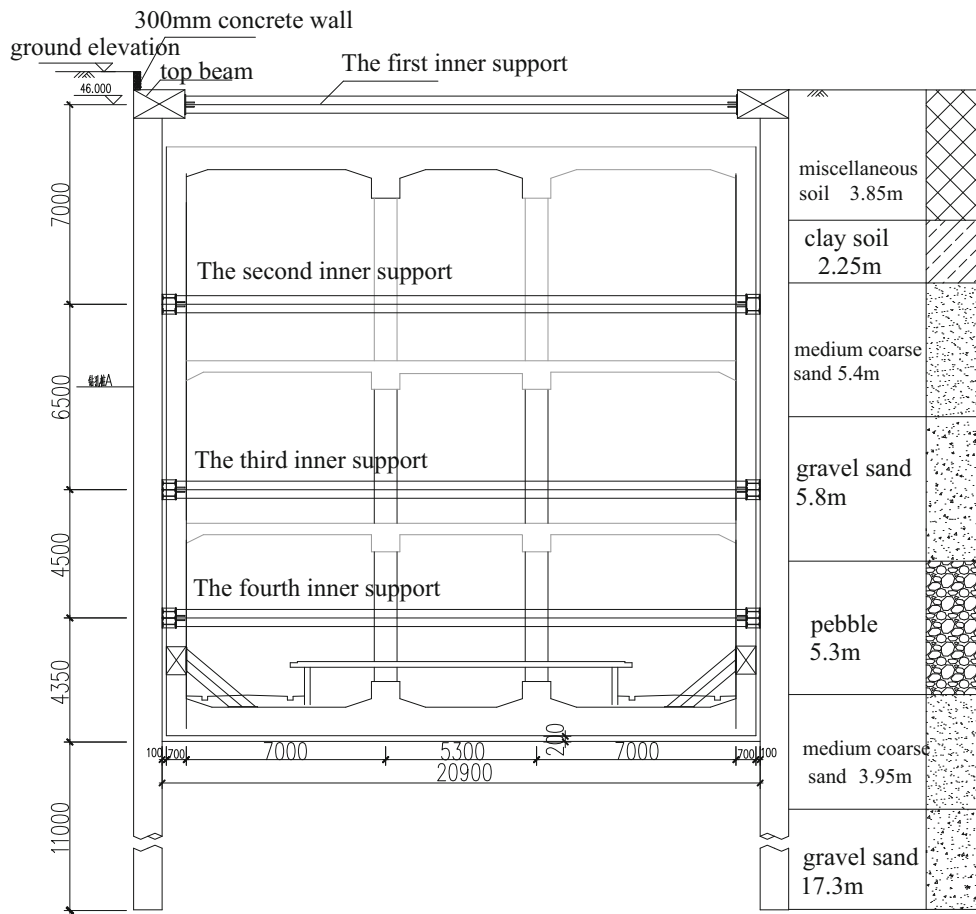


Fig. 2 Profile of braced excavation

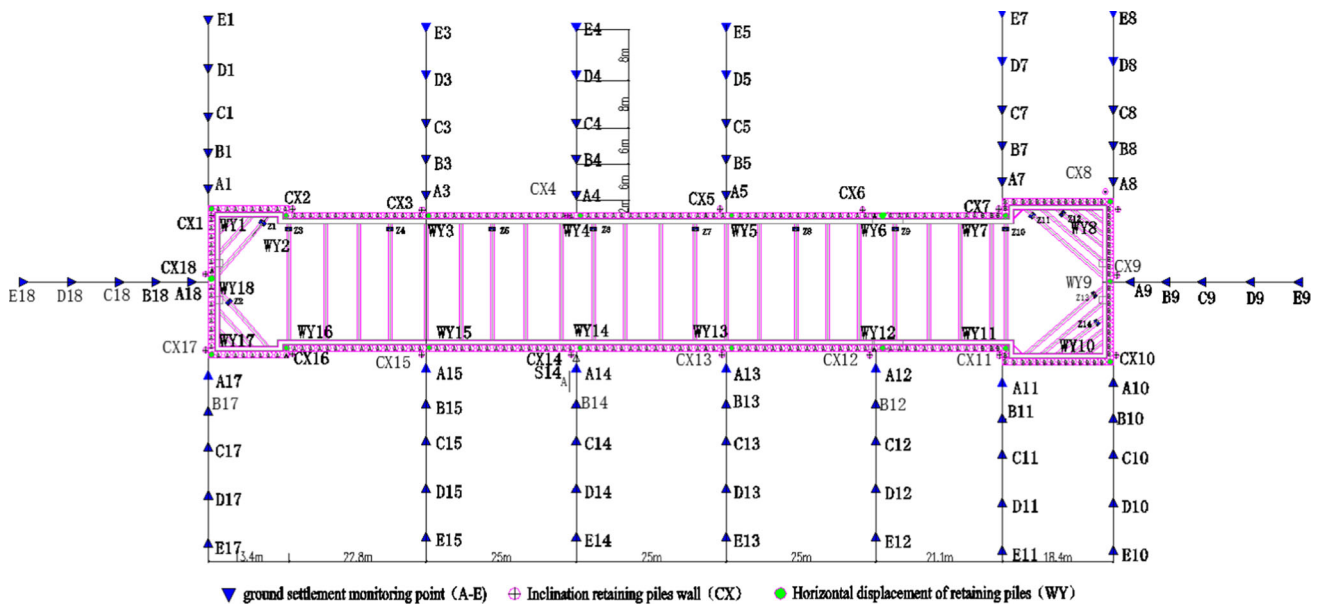


Fig. 3 Layout of monitoring point around the excavation pit

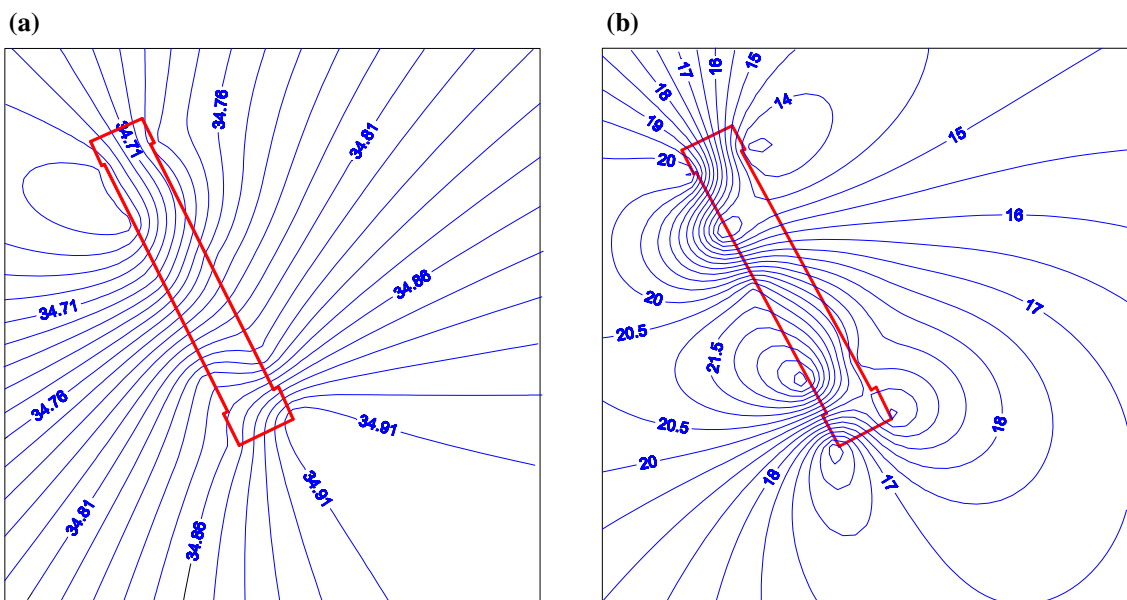


Fig. 4 Contour map of surrounding groundwater level in deep excavation (unit:m) **a** seepage fields of excavation pit before dewatering, **b** seepage fields of excavation pit after dewatering

recharge the groundwater under the excavation pit. At the end of the excavation, groundwater in surrounding area decreases to 13.42–24.03 m (Fig. 4b), the groundwater flows from southwest to northeast, the minimum groundwater head is at the northeastern corner of the excavation pit. Different groundwater head reflects different physical and mechanical properties of soils around the foundation pit, and different groundwater head difference of foundation pit corresponds to different soil settlement [1, 10–17].

Ground Settlement Rules Around the Foundation Pit

There are five monitoring intersections around the foundation pit during pumping, that is, A1–A18, B1–B18, C1–C18, D1–D18 and E1–E18, the distance from those monitoring wells to the edge of excavation pit is 2, 8, 14, 22 and 30 m respectively.

The planar distribution of ground settlement around the foundation pit is showed in Fig. 5, the maximum ground settlement is 14 mm and it decreases from the southwest to northeast after the excavation. The total ground displacement is in good agreement with the changing of groundwater head. With the increasing of excavation time, the settlement of each ground monitoring point of the pit is increasing. As the site continued pumping, pumping volume for each single well has been adjusted, the water level changed after excavating for 20 days and groundwater level rose. There is a slight rebound in the sand layer resulting in ground uplift at the settlement monitoring section A3 to E3, the uplift amount is 4.23 mm. Settlement

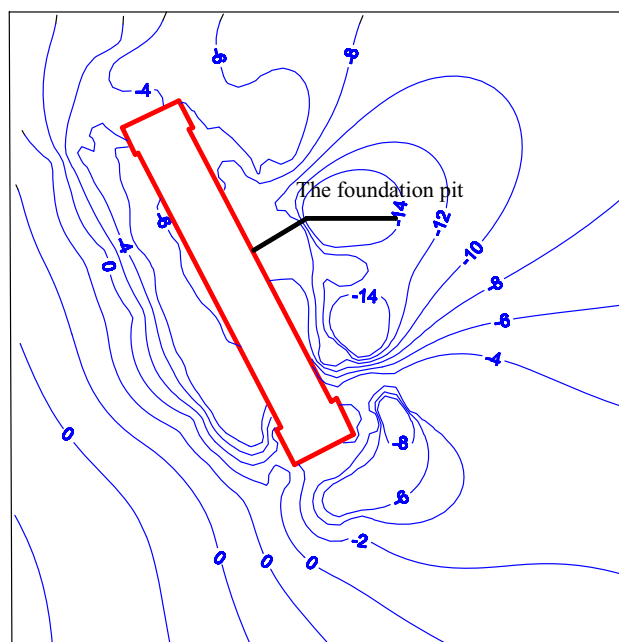


Fig. 5 Plane map of total settlement surrounding deep excavation pit (unit:mm)

observation point A3 is 2 m away from the edge of foundation pit, row piles and hanging concrete between the piles can effectively reinforce the soil, the minimum settlement is 0.17 mm, almost no settlement happens. B3 monitoring point is located 8 m away from the edge of the foundation pit, the cumulative ground settlement is 12.9 mm, and it is gradually reduced from settlement monitoring point C3 to E3.

A3 to E3 monitoring section is about 8 m from the foundation pit, and the maximum cumulative settlement is 12.9 mm. The largest settlement is appearing at about 30 m from the foundation pit, about 1.3 times of the excavation depth. It can be seen that dewatering will cause uneven settlement of the ground around the foundation pit, and the ground settlement is related to the physical and mechanical properties of soils around the foundation pit. The maximum ground settlement for this foundation is 14 mm, which was less than the maximum allowable settlement of 35 mm. The asymmetrical settlement of the foundation pit is because the decreasing height of dewatering is different.

Final Settlement of Different Monitoring Sections

Final settlement and impact scope of different monitoring sections (MS) 1, 6, 7, 8, 9 were analyzed. The horizontal distance from monitoring point to the edge of excavation pit is 2, 8, 14, 22, 30, 40, 50, 70 m respectively. The maximum ground settlement is at 22 m away from the edge of excavation pit (Fig. 6a), that is, the main impact distance is about 0.82H, and it is the same with existing study results by scholar Ou et al. [17]. As shown in Fig. 6, ground settlement is no longer increasing when the

distance from monitoring point to excavation is beyond 30 m, the ground settlement is only 0.6 mm at the monitoring point of 70 m. It can be concluded that the minor impact distance is from 1.74 to 3H. Ground settlement is almost 0 when the distance is beyond 3H.

The settlement rate can reflect the settlement distribution of each MS. Monitoring settlement in this project is compared with Panjin ground settlement curve in reference [6], Finno et al. [18] and technical manual of foundation engineering (Shanghai 2010). Scatter points in Fig. 7 are the changing of monitored settlement from point A3 to E3 during the excavation(Fig. 6b). The monitored settlement rule is in good agreement with reference [6] because the location of these two projects is the same, and they are in the same soil type and groundwater level. The main settlement impact scope is within 1.74H of the excavation pit, less than other experimental results (2H).

Ground Settlement of Different Monitoring Points at Same Monitoring Section

A3 to E3 monitoring section is selected in Fig. 7. Scatter points in Fig. 8 are the changing of monitored settlement from point A3 to E3 during the excavation. There is a

Fig. 6 a Ground settlement varies with different settlement monitoring point, **b** Comparison of different ground settlement and monitoring data

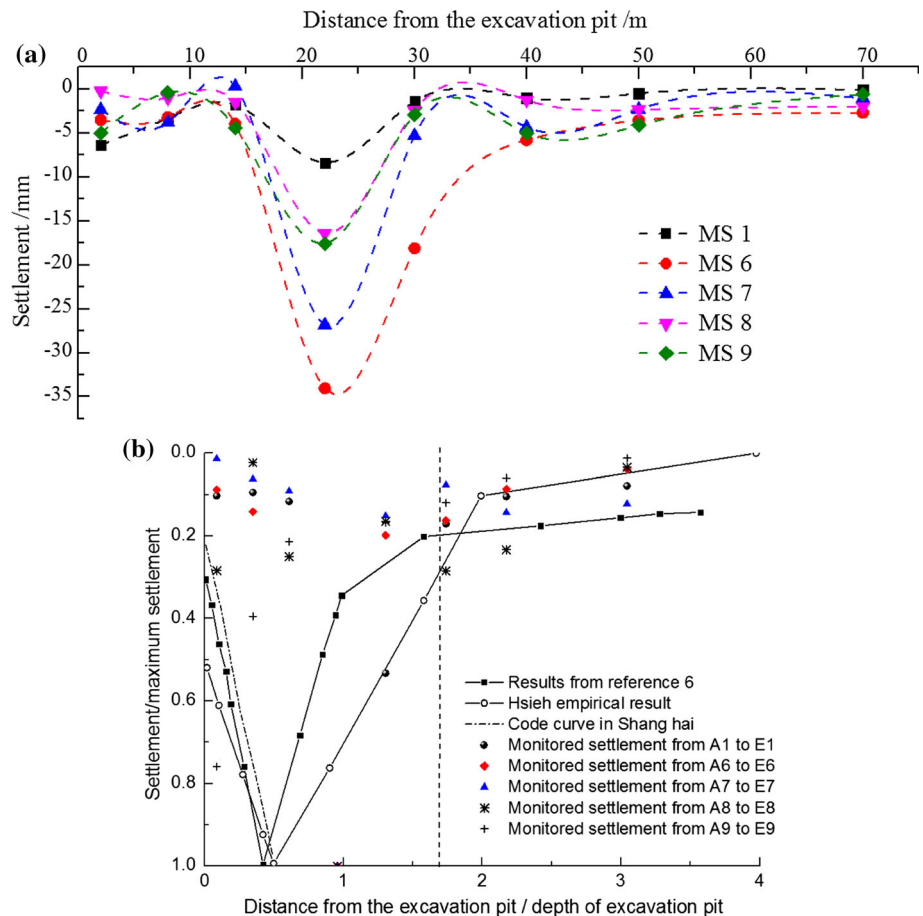


Fig. 7 Ground settlement varies with time in monitoring section A3–E3

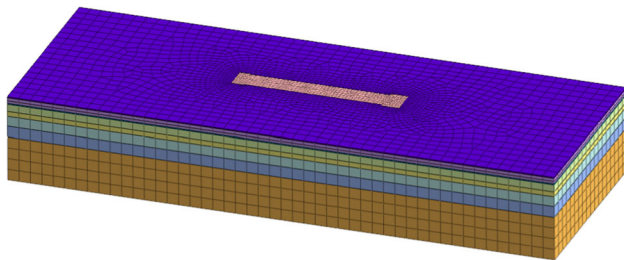
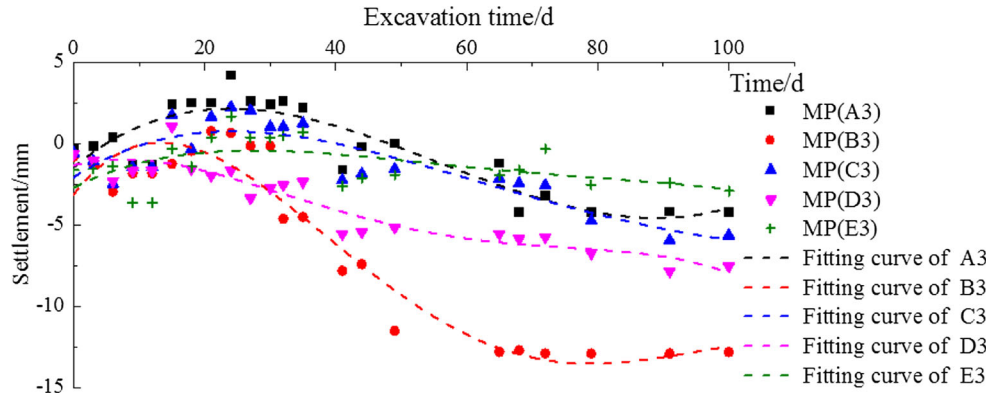


Fig. 8 Physical models of study area

slightly uplift of ground soil in the first 20 days of excavation and the maximum uplift value is 5 mm. The reason for this phenomenon is that the prestress steel bracing squeeze surrounding soils in the initial stage of excavation. With the excavation continuing, the positive soil pressure increases because of the unloading of inner soil in foundation pit, and the ground settlement is very obvious after 40 days excavation. Monitoring point (MP) A3 is 2 m away from the edge of foundation pit and the maximum settlement is only 4.18 mm, MP (B3) is 8 m away from the edge of foundation pit and the maximum settlement is 12.9 mm, settlement from C3 to E3 is between 4.18 and 12.9 mm. From the monitoring data of 18 monitoring lines, the maximum ground settlement is from 15 to 20 m, about 0.56 to 0.75H, while the maximum settlement of monitoring line A3 to E3 is at the point of 0.30H because the prestress is too small.

The dash lines in Fig. 8 shows the polynomial fit of A3 to E3. The ground settlement in each monitoring line obeys the 4th order polynomial, and the least squares method was used to fit the 4th order polynomial of A3 to E3. The expression of 4th order polynomial is assumed as follows,

$$S_{(M)} = a_0 + a_1 * t + a_2 * t^2 + a_3 * t^3 + a_4 * t^4 \quad (1)$$

where, $S_{(M)}$ is the ground settlement at each MP in different excavation period (unit: mm), a_0, a_1, a_2, a_3 and a_4 are undetermined coefficients, t is the excavation time (unit: d). The fitting curve from MP(A3) to MP(E3) can be written as (Eqs. 2-6):

$$S_{(A3)} = -1.42 + 0.34 * t - 0.01 * t^2 + 6.07e^{-5} * t^3 - 5.30e^{-8} * t^4 R^2 = 0.85 \quad (2)$$

$$S_{(B3)} = -3.11 + 0.53 * t - 0.03 * t^2 + 3.19e^{-4} * t^3 - 1.21e^{-6} * t^4 R^2 = 0.91 \quad (3)$$

$$S_{(C3)} = -2.04 + 0.26 * t - 0.01 * t^2 + 6.03e^{-5} * t^3 - 1.59e^{-7} * t^4 R^2 = 0.91 \quad (4)$$

$$S_{(D3)} = -1.31 + 0.11 * t - 0.01 * t^2 + 1.26e^{-4} * t^3 - 5.85e^{-7} * t^4 R^2 = 0.95 \quad (5)$$

$$S_{(E3)} = -2.67 + 0.20 * t - 0.01 * t^2 + 5.99e^{-5} * t^3 - 2.21e^{-7} * t^4 R^2 = 0.82 \quad (6)$$

The fitting results in Fig. 7 reveal that the measured settlement values are in good agreement with the fitting values when the quadratic polynomial method is adopted. The correlation coefficient R^2 is over 0.9. The changing rules of monitored settlement value from MP (A3) to MP (E3) can be obtained; ground settlement precaution system can be developed according to the changing rules of measured settlement data in order to assure the safety of excavation engineering.

Study on the Mechanism of Ground Settlement Caused by Excavation and Dewatering

Ground settlement is the interaction result of soil seepage field and stress field. It is closely related to the physical mechanical properties of soils, hydrogeological characteristics and dewatering process. For a strata unit, the vertical compression of soil is equal to the soil effective stress multiplying the volume compression coefficient [19–22]. Thus, the ground settlement S caused by dewatering can be written as follows,

$$S = \sum_{i=1}^n s_i = s_1 + s_2 + \dots + s_n \tag{7}$$

$$s_i = \Delta\sigma\alpha h_i = \gamma_w H h_i \tag{8}$$

where, s_i is the settlement of each layer, $\Delta\sigma$ is the effective stress increment, h_i is the thickness of each layer, H is the water drawdown of aquifer caused by pumping.

The classical seepage mechanics only consider the seepage effect without the deformation of soil skeleton. The soil skeleton under seepage pressure is compressed in the unsaturated soil, so the ground settlement caused by dewatering of foundation pit project cannot be completely ignored [23–26]. The seepage control equation considering the effect of strain is as follows,

$$\nabla[-k(\nabla h)] + n \frac{dS}{dh} \frac{\partial h}{\partial t} - S \delta_{ij} \frac{\partial \varepsilon_{ij}}{\partial t} = q_w \tag{9}$$

where, k is the permeability coefficient (m/s), h is the water head of seepage field (m), S is the saturability, q_w is the source term, that is, the quantity of groundwater, n is the void ratio. The finite element method is used to solve the coupled seepage-stress field basic equations.

Model Establishment and Parameter Selection

The model of foundation pit should be larger than the real project size in order to avoid the boundary effect on the simulation results. The thickness of soil layers considered in this model is three times larger than the depth of real excavation pit, that is, 75 m. The width and depth of soil layers in three-dimension-model is 250 and 125 m, respectively. The density of grids should be thick in the middle and thin in both sides in order to improve the computation efficiency. Normal constraints were set in this model, self-gravity stress was considered as initial stress except the ground was set as free surface. For the large scale of this model and large number of supporting piles in this project, equal stiffness transformation theory (Eq. 7) was used in this paper in order to simulate the piles in excavation pit. The guard piles were transformed to underground diaphragm wall and then the analysis was conducted. The underground diaphragm wall and soils were rigidly coupled by contact element.

The diameter of pile was assumed D , the distance from the middle of two piles to the edge of one pile was t , the thickness formula for underground diaphragm wall can be written as follows (Eq. 10),

$$\frac{\pi D^4}{64} = \frac{B h^3}{12} \tag{10}$$

where, $B = D+t$,

$$h = \sqrt{\frac{3\pi D^4}{16(D+t)}} \tag{11}$$

Parameters of piles are as follows $D = 1000$ mm, $t = 1400$ mm, the thickness and the depth of underground diaphragm wall is 0.74, 33 m respectively. From the geological investigation report, the initial groundwater level was set as -6 m. Ground water level decreased transiently after the computation of balance of initial ground stress and decreased to -25 m in five stages.

Through geological investigation report, the distribution of soil layers and physical mechanical parameters are showed in Table 1.

Comparison Between Calculated Settlement and Monitoring Settlement in Different Excavation Period

Modified Mohr–Coulomb model was adopted in finite element simulation method, fluid–solid coupling analysis of foundation pit excavation was conducted and the analysis results are showed in Fig. 9. The ground settlement increases with the excavation time, maximum ground settlement is 13.67 mm and it’s close to the monitoring data 12.14 mm. The subsider is at the position of $0.60H$ and it is at the monitoring position of $0.82H$. The monitoring data is in good agreement with simulated data in different excavation period.

Displacement of the Pile Wall

The pile wall at the south along the long side of the excavation pit was selected to investigate the ground displacement during dewatering and excavation (Fig. 10). As displacement of pile wall from monitoring point P10 to P17 shows, the pile wall is in heave states which reflect the fact that the rebound of soils at bottom of excavation will lift the surrounding pile walls. The ground settlement of pile cap is 1.09 mm after dewatering; the pile cap turns uplift of 0.57–1.39 mm during the initial period of foundation excavation because the sudden unloading of soil causes obvious rebound of soils at the bottom of the excavation. With excavation going to 40 days, the rebound of the soil at the foundation bottom will uplift the pile walls due to the large amount of soil unloading, but the settlement caused by dewatering will offset part of the pile wall lift and the maximum displacement is 2.79 mm. The uplift effect turns to dominate the displacement after excavation for 100 d. The deformation of pile cap increases regularly during the later period till to 120 d and the maximum displacement is 6.34 mm which is located at monitoring point P16. Monitoring points P11 and P16 are located at the corner of the

Table 1 Physical and mechanical parameters of surrounding soils

Types of soils	Thickness of soil layer (m)	Natural density (kN/m ³)	Cohesive force (kPa)	Inner friction angle (°)
Miscellaneous soil	3.85	18.5	10	5.0
Silty clay	2.25	18.5	12	6.5
Medium coarse sand	5.4	17.5	3	29.6
Gravel sand	5.8	20.3	2	33.0
pebble	5.3	20.5	2	34.0
Medium coarse sand	3.95	19.5	3	30.0
Gravel sand	8.05	20.1	2	33.0

Fig. 9 Comparison between calculated value and monitored value in different excavation period

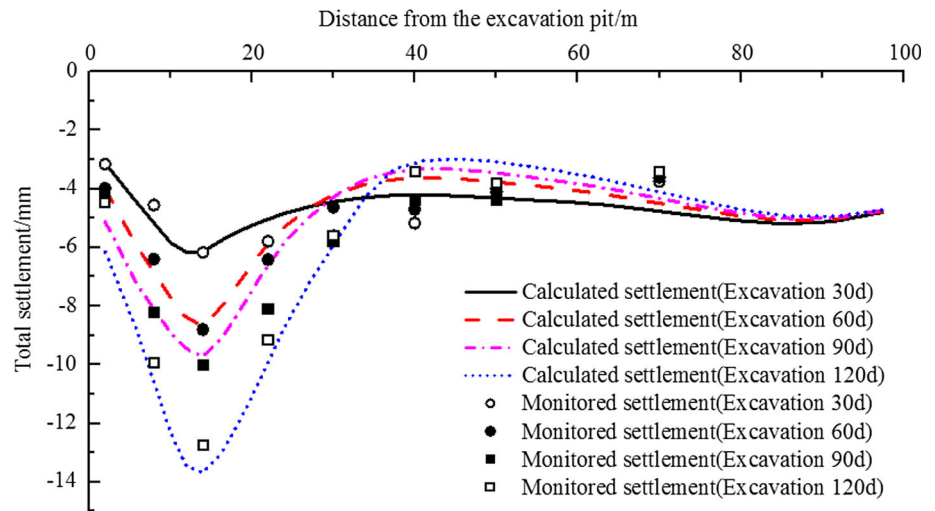
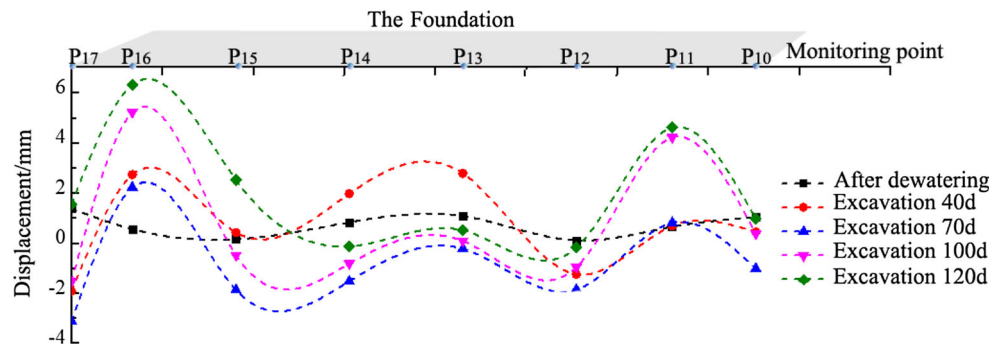


Fig. 10 Displacement of maintenance piles during excavation



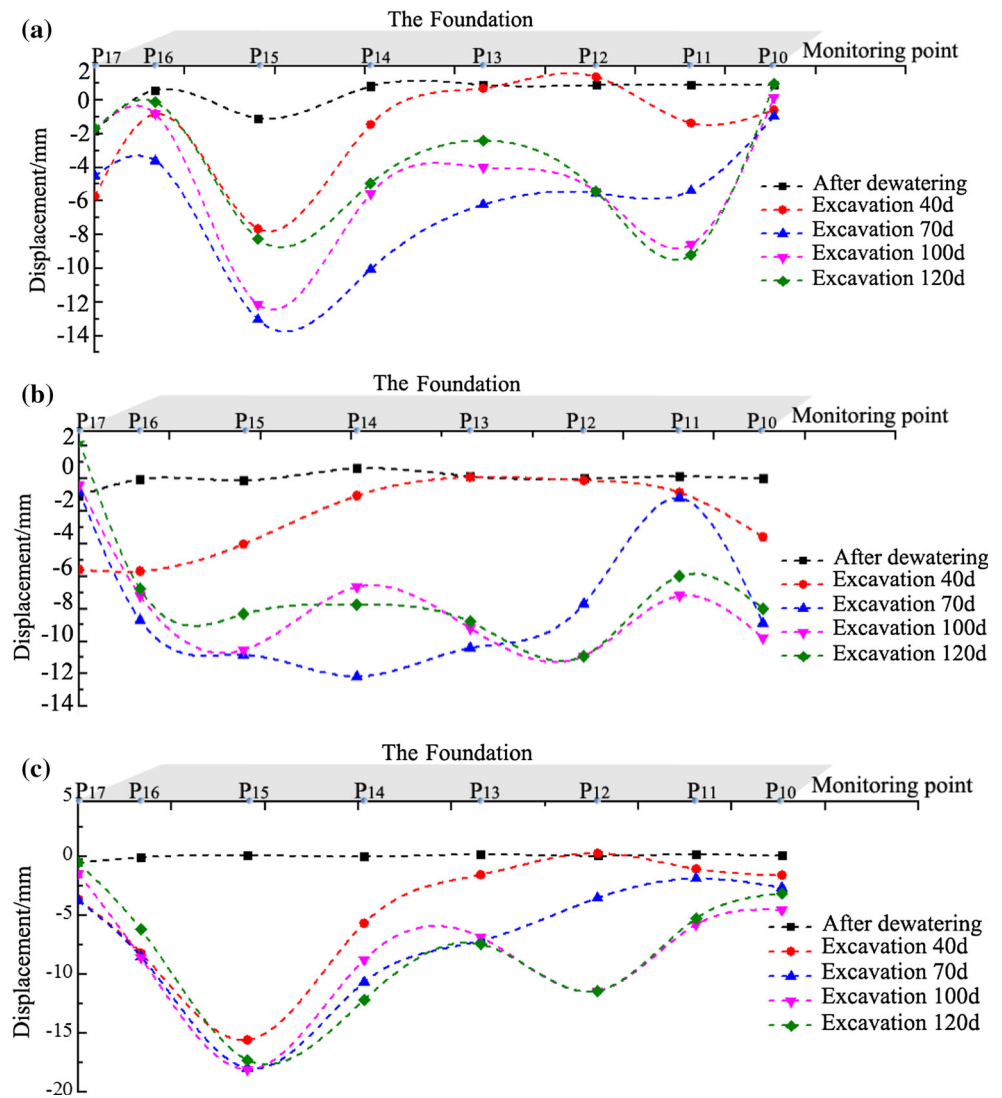
dumbbell-shaped foundation; it may bear bilateral uplift of the soils which will cause a double-peaked displacement.

Settlement of Each Monitoring Line in Different Stages

Figure 11 shows the settlement of monitoring line A–E in different excavation stages around the foundation pit. It can be seen from the figure that the settlement increases firstly and then decreases from the monitoring line A–E. The maximum settlement of the measuring point is 1.09 mm after dewatering; with the excavation days increasing, the

soil settlement gradually increased. At the period of 0–40 d, the largest ground settlement is at point P15 in monitoring line A and the maximum settlement value reaches 5.7 mm. Over excavation for 40 days, the maximum settlement location transfers to monitoring line C and no longer changes. The maximum ground settlement at each monitoring line A–E is 13.03, 10.83, 18.08, 5.67, 3.4 mm respectively. Overall, the ground settlement has time–space effect, in the early stage of excavation, the maximum settlement amount is close to the foundation edge; with the increasing of excavation depth, the location

Fig. 11 Ground settlement of each monitoring line
a Monitoring line A,
b Monitoring line B,
c Monitoring line C,
d Monitoring line D,
e Monitoring line E



of the maximum settlement location is gradually moving away from the foundation. The ground settlement is large at point P15 in each monitoring line because there are excessive load next to P15 during the excavation and the load surrounding excavation pit need to be cleaned in order to assure the stability of excavation. The ground settlement is larger in monitoring line C than other monitoring lines at later excavation stage, the maximum ground settlement is 18.08 mm, and it occurs at the distance of 22.8 m away from the foundation on the 100th day. Ground settlement in monitoring line E is the smallest compared with other monitoring lines which suits to the rule of subside.

Final Settlement at Different Buried Depths

The coupling model of seepage field and stress field during foundation excavation was conducted by finite element modeling. The north excavation pit was selected to analyze

the ground settlement as the foundation pit was a symmetrical structure. Figure 12 is the soil settlement of first, second and fourth steel support from the top to the bottom of the foundation pit. In vertical direction, the ground settlement decreases with the deepening of excavation, the maximum settlement of soil decreases from 13.7 to 7.72 mm in the first and last steel support, and the corresponding elevation is 0 and 25 m. The concrete surface built on the soil may fall apart from the soil because the ground settlement will increase continuously with the drainage continuing. The influence of settlement subsider is 50 m away from the edge of excavation pit in X direction. The maximum ground settlement is 14.16 mm caused by common influence of foundation excavation and dewatering. From 50 to 150 m, the ground settlement tends to stable and permanent, within 5 mm. This is because the effective stress is aggravated during dewatering and the settlement is induced by soil compression.

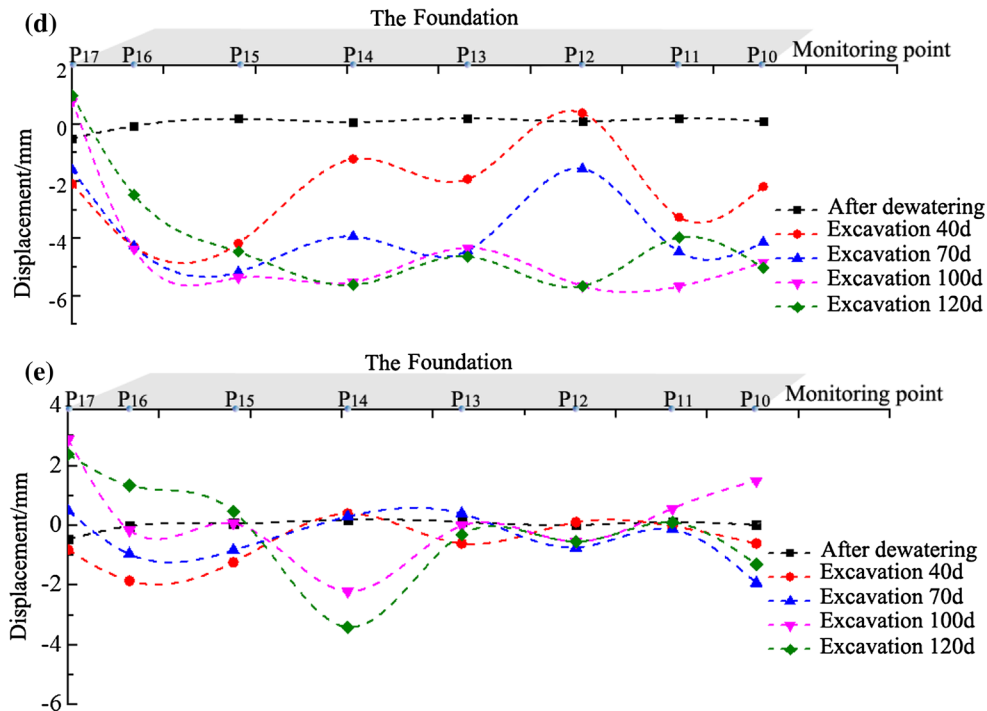


Fig. 11 continued

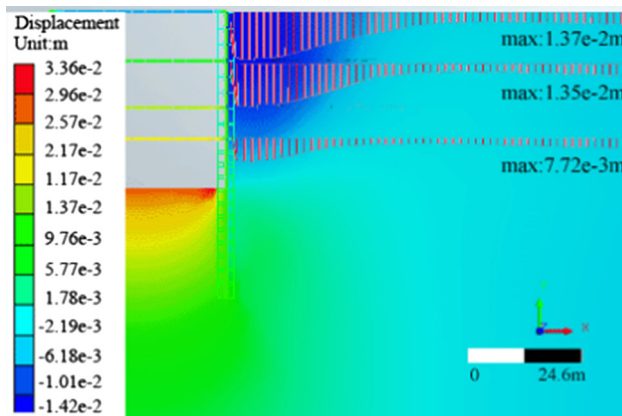


Fig. 12 Soil settlement in different layers

Ratio of Ground Settlement Caused by Foundation Excavation and Dewatering

Figure 13 is the fluid solid interaction analysis of ground settlement caused by foundation excavation and dewatering. The final settlement at the edge of excavation pit is 6 mm, the maximum ground settlement reaches 13.67 mm at the position of $0.60H$ from the edge of excavation pit, within the maximum settlement influence scope $0.56-0.75H$. The maximum ground settlement caused by foundation excavation and dewatering is 9.10 and 5.39 mm, accounts for 39.4 and 66.6%, respectively. The main impact scope of ground

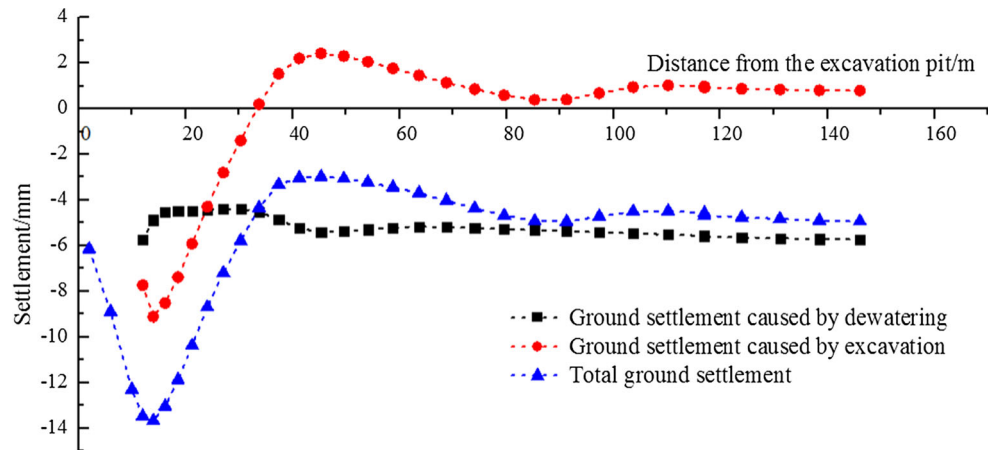
settlement during foundation excavation is at the range of $0.45-1.14H$, while the impact scope caused by dewatering is much more larger. It can be approximately considered that ground settlement 40 m away from the edge of foundation pit is generated by the foundation pit dewatering.

It can be seen that the ground settlement caused by foundation pit excavation is much larger than that caused by dewatering during the process of foundation pit excavation. However, the ground settlement caused by foundation pit dewatering can not be ignored.

Conclusions

1. Fluid–solid coupled analysis was conducted combining monitoring data and finite element simulation. The results show that, ground settlement forecast model established in this paper is full of practicability. The larger drawdown of groundwater, the larger ground settlement. Different water drawdown can cause uneven ground settlement.
2. The maximum ground settlement is 14 mm and it appears at the distance of $0.82H$, the ground settlement decreases after the subsider, the settlement impact scope of foundation excavation is about $2.3H$.
3. Ground settlement caused by foundation pit excavation in sandy area is about two times of that caused by foundation pit dewatering. The settlement of the

Fig. 13 Ground settlement caused by excavation and dewatering



excavation caused by foundation pit excavation accounts for the 66.6% of total settlement from 0.45 to 1.14H, ground settlement caused by dewatering was more compared to that of excavation beyond 1.14H.

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