The Influence of Different Excavation Methods on Deep Foundation Pit and Surrounding Environment

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Abstract. Taking a deep foundation pit in Shijiazhuang, Beijing as the background of the project, combined with the excavation range of the deep foundation pit and the spatial location and geometry of the surrounding engineering bodies, FLAC3D software is used to establish a numerical model of the deep foundation pit excavation containing the deep foundation pit, surrounding buildings and underground tunnels and other engineering bodies. The numerical model truly reflects the geometric size and spatial location relationship between deep foundation pit and surrounding engineering bodies. Based on the numerical model, the numerical simulation of deep foundation pit excavation under different excavation methods was carried out. The analysis of the horizontal displacement of the support structure during the excavation of the deep foundation pit, the investigation of the surrounding buildings and surface settlement and the deformation of the metro tunnel. The influence mechanism of different excavation methods on the safety of deep foundation pit, surrounding buildings and tunnel were discussed. It is concluded that the excavation method has less influence on the deformation and displacement of the deep foundation pit and the surrounding buildings and tunnels under the condition of shallow excavation depth. As the excavation depth increases, the effect of the excavation method on the deformation of the deep foundation pit, buildings, tunnels and surface settlement increases. The layered excavation method is suitable for deep foundation pits with shallow excavation depths, while the layered section excavation method is more suitable for deep foundation pits with deep excavation depths. Deep foundation pit excavation has a smaller effect on the deformation of the tunnel. The surrounding buildings have a greater influence on the deformation during the excavation of the deep foundation pit, but the effect of the buildings on it is less than the limiting effect of the prestressing anchor cables on the deformation of the deep foundation pit.

Keywords: Deep foundation pit · Different excavation methods · Complex engineering environment

1 Introduction

With the acceleration of urbanisation, the scale of deep foundation works is gradually becoming larger, and research into the depth and complexity of the project has become

a major development objective, while at the same time its safety issues are facing new challenges and problems [1–5]. The safety of deep foundation pit is facing new challenges and problems. In recent years, deep foundation pit stability problems occur from time to time, especially in some deep foundation pit projects with complex environment and difficult support, which has caused great harm to China's economic and social stability [6–10].

Deep foundation pit has obvious spatial effect, which has a serious impact on the deformation and stability of deep foundation pit [11–13]. In recent years, scholars have done extensive research work on the safety of deep foundation pit. For example, Jianhang Liu launched an analysis of deep foundation pit deformation based on the application of spatial effect theory to explore the influence of the soil itself on the control of deep foundation pit deformation, in order to achieve the purpose of controlling deep foundation pit deformation by using the law of soil change [14]. Ruiwu Qi et al. studied the the effect of deformation of the enclosure structure itself and the deformation of different locations around the deep foundation pit under different working conditions of the giant deep foundation pit [15]. Based on the field measured data, Peixin Wang et al. analysed the deformation law, settlement causes and control measures of subgrade and foundation pit [16]. Jiangtao Liu et al. established a three-dimensional deep foundation pit model, studied the deformation law of deep foundation pit excavation based on different constitutive models, and analysed the law of surface settlement and retaining structure deformation [17]. John simulates the displacement and deformation of a square deep foundation pit without enclosure structure based on linear elastic and finite element analysis methods [18]. Mana and Clough analysed different widths of deep foundation pits based on the two-dimensional finite element method to reveal the relationship between the lateral displacement of deep foundation pits and the change of excavation width [19]. Wong and Broms used a two-dimensional finite element method to establish a deep foundation excavation model to explore the effects of various factors on the deformation of the deep foundation pit,including the form and stiffness of the support structure, the depth of entry, and the depth and width of the excavation [20]. By focusing on the spatial effect, other scholars have revealed the influence law of deep foundation pit geometric size, length width ratio, support structure, construction sequence, construction method and stiffness of support on deep foundation pit deformation [21–25].

The above research results are important for people to understand the deformation characteristics of deep foundation pit enclosure structures, the ground settlement pattern and the influence mechanism on the safety of the surrounding environment. At present, the research on the deformation law of deep foundation pit mostly focuses on the support form and excavation sequence of deep foundation pit, while there is little research on the impact of the excavation method on the deformation of the foundation pit itself and the safety for the surrounding structures [26–28]. People have insufficient understanding of the deformation of deep foundation pit under different excavation methods and its impact on the safety of surrounding environment, which needs to be further studied.

This paper takes a deep foundation pit in Shiliuzhuang, Beijing as the engineering background, and uses FLAC3D software to conduct numerical engineering simulation research in a complex environment, and analyzes the deformation law of the deep foundation pit by changing the excavation method to reveal the influence mechanism of

different excavation methods on the safety of the deep foundation pit on its surrounding tunnels and buildings.

2   Introduction to Numerical Simulation Method

FLAC (Fast Lagrangian analysis of continua) is an English numerical simulation software based on the finite difference method. The software has a simple interface, easy operation and powerful operation, which greatly saves cost and time compared with traditional experiments. FLAC3D is widely used in the field of geotechnical engineering because it contains a comprehensive material model, flexible solution method, accurate results, and can meet various engineering problems. velocity, plastic state and other internal variables that cannot be obtained from real experiments. In addition, the post-processing function of FLAC3D is also powerful, users can directly get the stress and displacement diagrams of the simulated objects, which can express the engineering problems in a more intuitive and concise way.

3   Project Overview and Geological Conditions

Based on the background of a deep foundation pit to be excavated in Shiliuzhuang, Beijing, the surrounding environment of the deep foundation pit is relatively complex. The west side is close to a 6-storey residential building with a horizontal distance of 4 m; On the east side has a subway tunnel, horizontal distance of 16 m, 12 m in buried deeply. Excavation scope is 56 m long, 40 m wide. Figure 1 is the plane position of deep foundation pit.
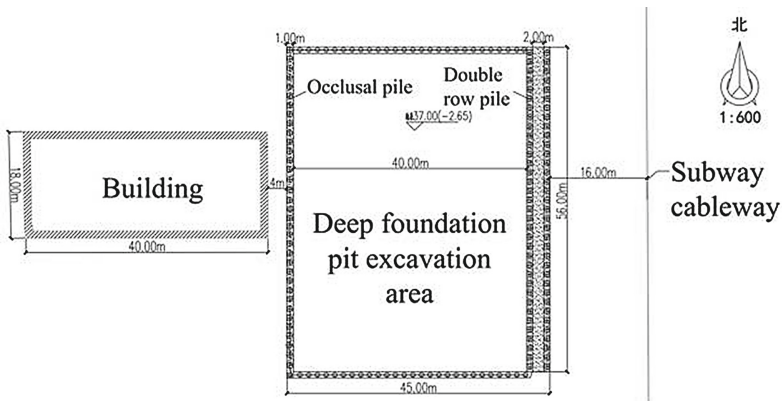
Plan location of deep foundation pit

Fig. 1. Diagram of plane location of deep foundation pit.

According to the survey data provided on site, the deep foundation pit and surrounding buildings and subway tunnel are located from the surface. The stratum can be divided

into 7 layers according to different lithology, including Miscellaneous soil layer, Clay silt layer, Silty clay layer-1, Fine medium sand layer-1, Silty clay layer-2, Fine medium sand layer-2 and Pebble layer. The thickness and mechanical parameters of different strata are shown in Table 1.

Table 1. Stratum thickness and mechanical parameters.

| Soil layer name	Thickness (m)	Cohesion (KPa)	Density (KN/m^3)	Elastic modulus (MPa)	Poisson's ratio	Tensile strength (KPa)
Impurity soil	1	10	18	30	0.30	5
Clayey silt	1	23	19.7	17	0.29	11.5
Silty clay-1	7	15	19.9	21	0.29	7.5
Medium fine Sand-1	4	0	20	38	0.28	0
Silty clay-2	6	26	20	22	0.29	13
Medium fine Sand-2	5	0	20.4	40	0.28	0
Pebble	14	0	22	60	0.27	0

4   Numerical Model of Deep Foundation Pit Excavation

With the purpose of studying the influence of diverse excavation methods on the safety of deep foundation pit and surrounding environment, a numerical model containing engineering bodies such as deep foundation pits, surrounding buildings and underground tunnels was established using numerical methods based on information such as the actual spatial location distribution and geometric dimensions of the proposed excavation range of deep foundation pits and surrounding engineering bodies, which can truly reflect the deep foundation pits and surrounding engineering.

4.1   Numerical Model Dimensions of Deep Foundation Pit

The size of the numerical model for the pit under study are selected in this paper taking into account the influence of spatial effects. If the size of the established model is too small, it will cause the deformation of itself and the surrounding engineering body to be bounded by the boundary conditions, resulting in size effects; if the model size is too large, it will lead to an infinite increase in computation time, which can be reduced by increasing the number of meshes, but will reduce the computation accuracy. Increasing the number of grids can reduce the calculation time, but the calculation accuracy will be reduced. According to the research, the range of surface settlement caused by general deep foundation pit excavation is about 3 times of the excavation depth of deep

foundation pit. In this paper, we not only consider the proposed excavation depth but also the geometric information of the surrounding engineering body, and the established geometric model of deep foundation excavation is 151 m in length, 56 m in width, 38 m in height, and 11.5 m in depth of deep foundation excavation. The geometric model is meshed and optimized, and the number of optimized grid elements is 2.58 million. Figure 2 shows the deep foundation pit excavation calculation model established by us. The figure clearly shows the excavation scope of the proposed deep foundation pit, the stratum of the area and the spatial location of surrounding buildings, subway tunnels and other engineering bodies.
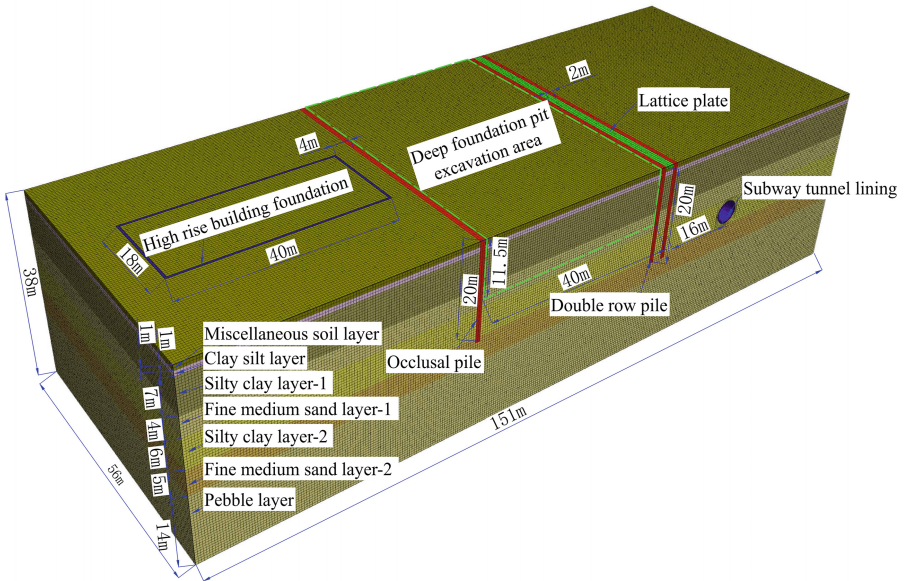

Fig. 2. Numerical model of deep excavation.

4.2   Pile Anchor Support Structure and Surrounding

This paper presents a numerical simulation modelling of a solid unit support system using a deep foundation support method with pile-anchor support. The outer diameter of the underground tunnel lining on the east side of the deep foundation pit is 3 m. On the side of the deep foundation pit adjacent to the tunnel, a double-row pile + anchor cable support system + slurry flower pipe is used, with a double-row pile diameter of 1 m, a pile spacing of 1.5 m, a pile length of 20.0 m and a row spacing of 3.0 m. A lattice plate is connected between the double-row piles, with a lattice plate size of 56 m in length, 2 m in width and 0.5 mm in height. A total of 1 anchor cable and 4 grouting pipes are arranged with a horizontal spacing of 1.5 m and a vertical spacing of 2 m. There are buildings on the west side of the deep foundation pit, 40 m long and 18 mm

wide. In the immediate vicinity of the building side using the occlusion pile + anchor cable support system, occlusion pile diameter 1mm, pile spacing 1.5 m, pile length of 20.0 m. A total of 3 anchor cables are arranged, with a transverse spacing of 1.5 m and a longitudinal spacing of 3 m. Figure 3 shows a partial enlarged view of the numerical model of the pile anchor support system, in which the geometric information and spatial location of the pile anchor support system, surrounding buildings and tunnels are marked in detail. It should be noted that the model has been simplified to take into account the complexity of the model by converting the double-row piles and the occluded piles into a ground link wall in accordance with the principle of flexural stiffness equivalence, and the modulus of elasticity of the ground link wall is taken as 70% of the modulus of elasticity of the double-row piles and the occluded piles selected by the piles. Even the wall is 1 m in width, consistent with the diameter of the pile; even the wall depth to 20 m, and is consistent with the length of the pile.
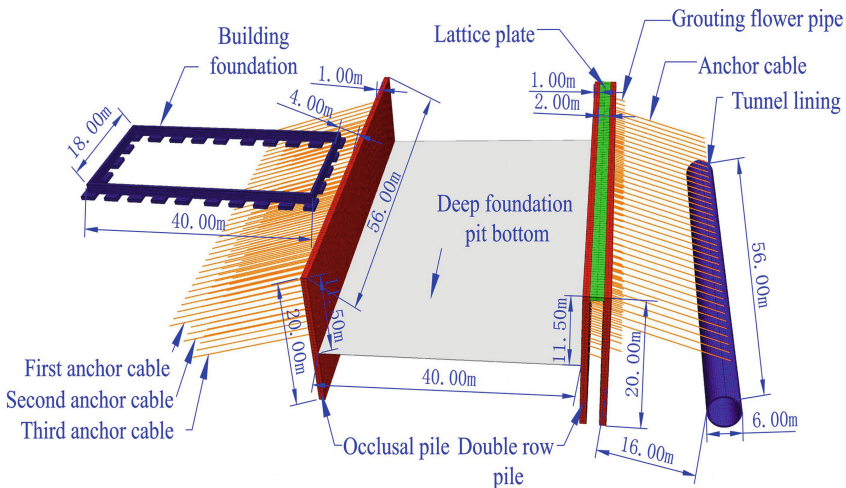
Fig. 3. Local enlarged view of numerical model of pile-anchor support system.

4.3 Basic Assumptions, Boundary Conditions and Material Parameters

The following assumptions have been made in the modelling and calculations with the aim of removing the effects of some minor factors, while ensuring that the results are accurate:

- Assume that the soil is isotropic and homogeneous elastic plastic body.
- It is assumed that building foundation, tunnel lining, lattice plate and diaphragm wall (double row pile and bite pile) are ideal linear elastomers.
- Different types of piles (such as cast-in-place piles, rotary jet grouting biting, etc.) have different soil penetration processes. The soil penetration process of piles is not a completely static process, involving large deformation problems, and the stress state

will change. Since the deep foundation excavation is the focus of this simulation, the process of pile entry is ignored in this simulation.

- When applying boundary conditions, the full displacement constraint is applied at the bottom of the whole model, the top of the model is a free surface, and the normal displacement constraints are applied on the sides around the model. The building on the west side is converted into gravity load and applied to the building foundation, with a total of 108 MN. The effect of gravity is considered in the whole model.
- Mohr Coulomb criterion is adopted as the constitutive model of stratum soil material. See Table 1 for the selection of soil material parameters. Concrete material with strength grade of C25 is selected for building foundation and lattice plate, and concrete material with strength grade of C25 is also selected for diaphragm wall (double row pile and bite pile), but its elastic modulus is 70% of C25 concrete elastic modulus according to the principle of equivalent flexural stiffness, The subway tunnel lining is made of concrete with strength grade of C40. See Table 2 for the mechanical parameters of concrete with each strength grade. See Table 3 for the material parameters of the anchor cable and grouting flower pipe model adjacent to the east of the subway tunnel and the three anchor cables model adjacent to the west of the building.

Table 2. Mechanical parameters of supporting structure materials.

Structure name	Concrete strength	Elastic modulus (GPa)	Poisson's ratio
Diaphragm wall (double row pile, bite pile)	C25	19.6	0.2
Tunnel lining	C40	32.5	0.2
Foundation and lattice plate	C25	28	0.2

4.4 Calculation Conditions

Before the deep foundation pit model is excavated, the initial stress balance calculation is carried out for the overall model, that is, the stress balance of the overall model is calculated under the simultaneous action of the self-weight of the building and the model as a whole, and the displacement is cleared to zero after the calculation. Then the deep foundation pit excavation calculation is carried out, and the excavation is carried out in layers along the vertical direction, 1.5 m per layer, one layer at a time, and divided into four excavation areas along the horizontal direction, as shown in Fig. 4. To study the effects of different excavation methods, this paper adopts two methods for excavation:
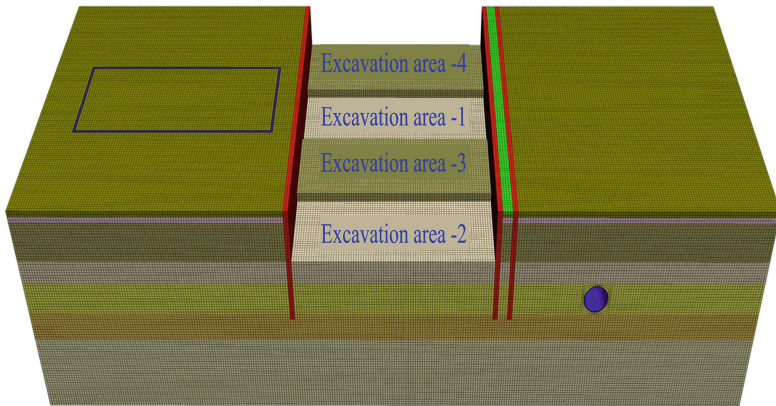
Method 1: Layered excavation, that is, the four excavation areas excavate one layer as a whole, and then construct the anchor cable and grouting flower pipe in Zone 1 and Zone 2, and then the anchor cable and grouting flower pipe in Zone 3 and Zone 4. This is repeated until the 11.5 m deep foundation pit is excavated in 8 layers, a total of 8

Table 3. Mechanical parameters of anchor cable and grouting flowered pipe structural materials.

Name		Incident angle	Total length (grouting section) (m)	Pre applied axial force (KN)	Elastic modulus (GPa)	Tensile strength (GPa)	Perimeter of grouting hole(m)
Grouting flower pipe		15°	6(6)	/	206.0		0.471
East anchor cable		15°	22(17)	300	205.0	7.44	0.471
The west side	First way	15°	26(17)	400	205.0	7.44	0.471
	Second way	15°	24(18)	450	205.0	7.44	0.471
	Third way	15°	23(18)	430	205.0	7.44	0.471

Note: The bonding stiffness of the grouting section of anchor cable and grouting flower pipe is 560 MN/m, the bonding strength is 0.15 MP/m, and the bonding friction angle is 25°; The bond strength of the free end of the anchor cable is considered to be 0 MP/m and the adhesive friction angle is 0°

Fig. 4. Diagram of four excavation areas of deep foundation pit.

calculation conditions. Method 2: Excavate in layers and sections, that is, excavate one layer at the same time in Zone 1 and Zone 2, and then construct the anchor cable and grouting flower pipe in Zone 1 and Zone 2; Then excavate one layer in Zone 3 and Zone 4 at the same time, and then construct the anchor cable and grouting flower pipe in Zone 3 and Zone 4. Repeat this until the 11.5 m deep foundation pit is excavated in 8 layers, a total of 16 calculation conditions.

5 Impact of Different Excavation Methods on Deep Foundation Pit and Surrounding Environment

Based on the previously established numerical model, under different excavation methods was carried out to analyse the horizontal displacement of the support structure, the settlement of surrounding buildings and ground surface and the deformation law of subway tunnel in the process of deep foundation pit excavation are analyzed, and the influence mechanism of different excavation methods on the safety of deep foundation pit, surrounding buildings and tunnel is discussed.

In order to fully investigate the settlement displacement and deformation pattern of the deep foundation pit, surrounding buildings and tunnels during excavation, multiple displacement measuring points and lines are set on the model. Firstly, in order to detect the deformation of the deep foundation pit during excavation, a measuring point is arranged in the middle of the top of the support structure on the west side of the deep foundation pit, numbered ZH-1 respectively, and three vertical measuring lines are arranged at an equal interval of 22 m on the support structure, numbered SC-X1, SC-X2 and SC-X3. One measuring point, numbered ZH-2, is arranged in the middle of the top of the support structure on the east side. Two vertical measuring lines, numbered SC-X4 and SC-X5, are arranged on the support structure at an interval of 44 m. In order to detect the settlement and displacement of the building and its surrounding surface, two measuring points are arranged at an interval of 25.2 m on the foundation of the north side of the building, numbered JZ-1 and JZ-2 respectively. On the surrounding surface, two measuring lines are symmetrically arranged on both sides of the building along the east-west direction, 11 m away from the building, numbered DB-X1 and DB-X2. In order to explore the deformation and displacement of the subway tunnel, a survey line, numbered SD-X1, is arranged along the tunnel direction on the side of the tunnel close to the deep foundation pit, and a survey line, numbered SD-X2, is also arranged at the top of the tunnel. Two survey lines, numbered DB-X3 and DB-X4, are arranged along the east-west direction on the surface above the tunnel at an interval of 40 m. Two survey points, numbered DB-1 and DB-2, are arranged on the surface between the two survey lines at an interval of 13 m. The detailed layout is shown in Fig. 5.
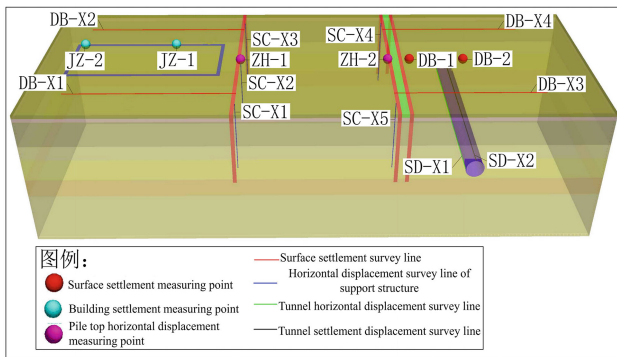

Fig. 5. Layout diagram of measuring points and lines.

5.1 Effect of Deep Foundation Pit Excavation on Deep Foundation Pit Deformation

The horizontal lateral displacement of the supporting structure on both sides of the deep foundation pit can reflect the overall deformation of the deep foundation pit. In order to analyze the deformation of the deep foundation pit under the two excavation methods after all excavation along the depth of 11.5 m.

Figure 6 shows the horizontal displacement diagram of the foundation pit after excavation. Figure 7 shows the horizontal displacement curves of the measured lines of the support structures on the east and west sides of the pit after excavation. Figure 8 shows the measured results of horizontal displacement of supporting structures.

(a) Layered excavation method   (b) Layered section excavation method
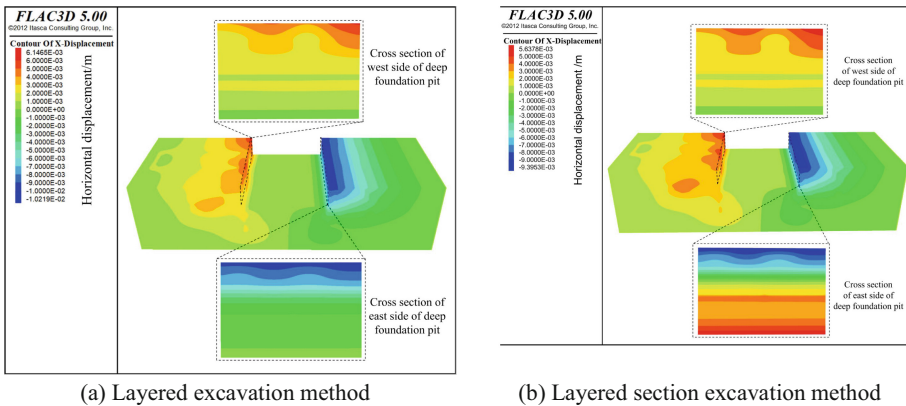
Fig. 6. Horizontal displacement of deep foundation pit.
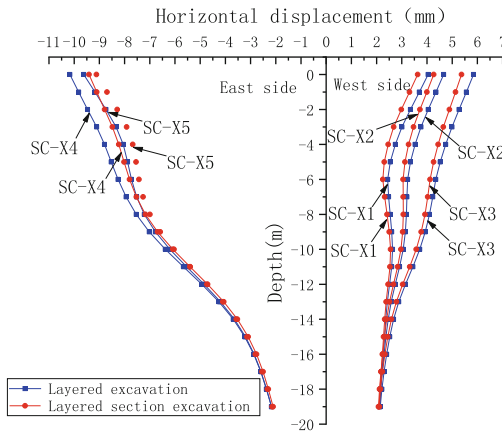
Fig. 7. Numerical results of horizontal displacement of retaining structure.

It can be seen from Fig. 6 and Fig. 7 that when the excavation is carried out in accordance with the depth of 11.5 m, the largest displacement of the support structure on

both the west and east sides of the deep foundation pit under the two different excavation methods occurs at the top of the deep foundation pit, and the horizontal displacement on both the east and west sides of the deep foundation pit show a trend of gradual reduction as the depth increases. As can be seen from Fig. 7, the maximum horizontal displacement on the west side is 5.85 mm, and the maximum horizontal displacement on the east side is 10.22 mm, which is significantly greater than that on the west side, with a difference of 4.37 mm. Analysing the reasons for this, three prestressing anchor cables were applied during the support of the western side of the deep foundation pit as the western side was adjacent to the building, while one prestressing anchor cable was applied for the metro tunnel which was farther away from the deep foundation pit. It is obvious from the curves in Fig. 7 that the horizontal displacements on both sides under the layered section excavation method are overall smaller than those under the layered excavation method, so the layered section excavation method has less influence on the deformation of the deep foundation pit. As the calculation in this paper assumes that whichever excavation method is used, the prestressed anchor cables in Zone 1 and Zone 2 are excavated first, and then the prestressed anchor cables in zone 3 and zone 4 are constructed. The first applied anchor cables limit the deformation of the supporting structures in Zone 1 and Zone 2, so the horizontal displacement of the survey lines in Zone 1 and Zone 2 is less than that of the survey lines in Zone 3 and Zone 4. This can be clearly seen in Figs. 6 and 7. It should be pointed out that the west side of deep foundation pit Numbers for SC - X2 line, fall in the area of SC - X2 line located close to the side of the building. Due to the influence of the building's self-weight, the horizontal displacement of the SC-X2 measuring line is greater than that of the SC-X1 measuring line falling in Zone 1. It can be seen that the building still has a great impact on the deformation of the deep foundation pit. The overall horizontal displacement of the measurement line SC-X3 is greater than the horizontal displacement of the measurement line SC-X2, and it can be concluded that the effect of the building on the deformation of the deep foundation pit is less than the limiting effect of the prestressing anchor cable on the deformation of the deep foundation pit.

To verify the validity of the numerical simulation results, the horizontal displacement of the excavation was monitored during excavation, and the measurement lines were arranged in the same way as the numerical simulation. Through comparison, the trend of the horizontal displacement curve of each measurement line in the numerical simulation results matches well with the field monitoring data, thus verifying the accuracy of the numerical simulation.

In order to further analyze the influence of different excavation methods on the deformation law of deep foundation pit in the excavation process, Fig. 9 shows the relationship curve of the horizontal displacement of the top measuring points of the support structure on the east and west sides with the excavation depth under different excavation methods. The numerical simulation curve and field measured curve are given in the figure. The field measured data are in good agreement with the numerical simulation results. As can be seen from the diagram, the horizontal displacement at the top position of the deep foundation support structure under both excavation methods gradually increases as the excavation depth increases. At shallow excavation depths there is little difference in the horizontal displacement of the deep foundation pit caused by the two excavation

methods. But when the excavation depth increases to a certain value, the horizontal displacement under layered excavation begins to be greater than that under layered section excavation. The critical value in the east is 3 m and that in the west is 7.5 m. It is not difficult to conclude that the reinforcement effect of anchor cables can weaken the effect of excavation methods on the deformation of deep foundation pits. The difference of horizontal displacement between the two excavation methods increases with the increase of excavation depth. The horizontal displacement under layered excavation method is greater than that under layered and segmented start method. In summary, it can be concluded that the layered excavation method is suitable for excavating shallow deep pits, while the layered section excavation method is more suitable for deeper deep pits.
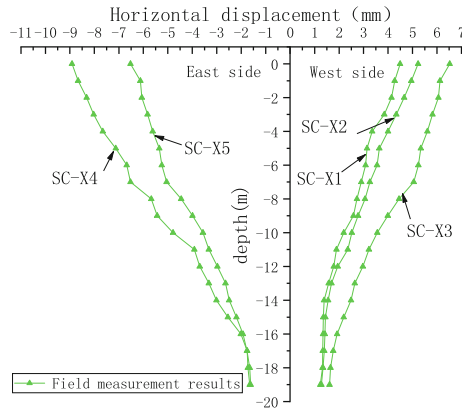
Fig. 8. The measured results of horizontal displacement of supporting structures.

5.2   Impact of Deep Foundation Pit Excavation on Buildings and Surrounding Surface

5.2.1   Impact on Surface Settlement around Buildings

The excavation of deep foundation pit will inevitably cause the settlement of adjacent buildings and surrounding surface. In the process of excavation, when the settlement displacement of buildings and surrounding surface reaches a certain range, it will affect the normal use, and more serious settlement will lead to safety accidents. Analyze Fig. 10, the settlement displacement curve of the ground surface around the building after the excavation of the deep foundation pit, to investigate the effect of different excavation methods on the settlement displacement of the ground surface around the building.

As can be seen from Fig. 10, when the deep foundation pit is fully excavated, whether it is excavated in sections or in layers and sections, the surface settlement displacement decreases as the surface position is far away from the deep foundation pit. At a distance of 2 m from the deep foundation pit, the curve shows an extreme value, indicating a large settlement of the ground surface in the middle position due to the combined effect of the building and the deep foundation pit. The maximum surface settlement displacement
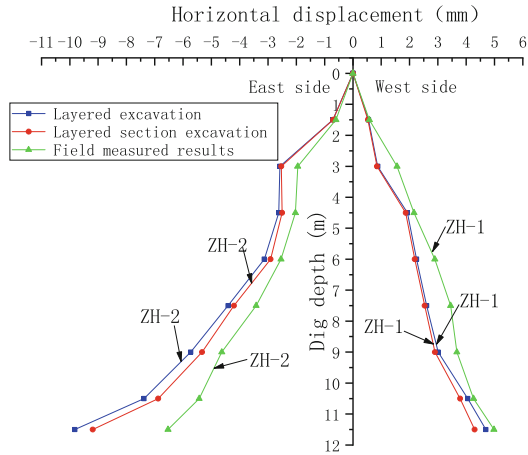
Fig. 9. The relation curve between the horizontal displacement of the top of the supporting structure and the excavation depth.
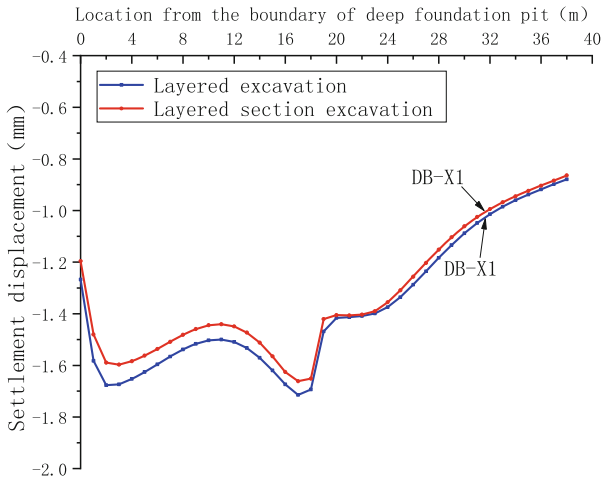
Fig. 10. The surface settlement displacement curve around the building.

occurs at 17 m, with a maximum of 1.71 mm for layered excavation and 1.67 mm under layered section excavation. By comparing the curves under the two excavation methods, it can also be seen that the overall surface settlement displacement under the layered section excavation method is less than that under the layered excavation. The closer it is to the boundary of the deep foundation pit, the more obvious this phenomenon is. It can be seen that different excavation methods have a greater influence on the surface settlement around the deep foundation pit. Compared with the layered excavation method, The layered section excavation method has less impact on the surface settlement and displacement and is safer, which is consistent with the conclusion obtained from the above analysis of deep foundation pit deformation.

5.2.2 Impact on Building Settlement

To analyze the effect of different excavation methods on the settlement of buildings, Fig. 11 shows the settlement displacement diagram of the building after deep foundation pit excavation, and Fig. 12 shows the relationship curve between building settlement displacement and excavation depth.

Whether it is layered excavation or layered section excavation, when the excavation is complete, the closer the building settles to the deep foundation pit, the less it settles, while on the side furthest from the deep foundation pit, the building settles to a maximum. The reason is that there is anchor cable reinforcement in the soil close to the deep foundation pit, and the overall performance of the soil is better. In the absence of anchor cables in the soil away from the deep foundation, the building settles and displaces more under the self-weight of the building. The maximum settlement of buildings under layered excavation is 4.3 mm, and the maximum settlement under layered section excavation is 4.12 mm. It can be seen that layered excavation has a greater impact on building settlement. With the increase of excavation depth, the settlement displacement of buildings also increases. When the excavation depth is shallow, the settlement displacement of buildings under the two excavation methods is almost the same. When the excavation depth increases, the settlement displacement of buildings under layered excavation method is significantly greater than that under layered section excavation method. By analyzing the influence law of building settlement, it can also be concluded that the layered excavation method is suitable for shallow and deep foundation pit, and the layered and section excavation method is more suitable for deeper deep foundation pit.
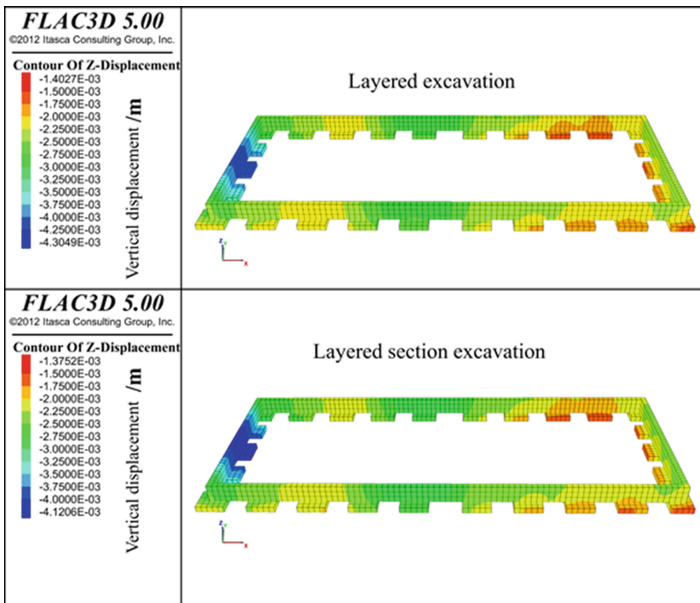

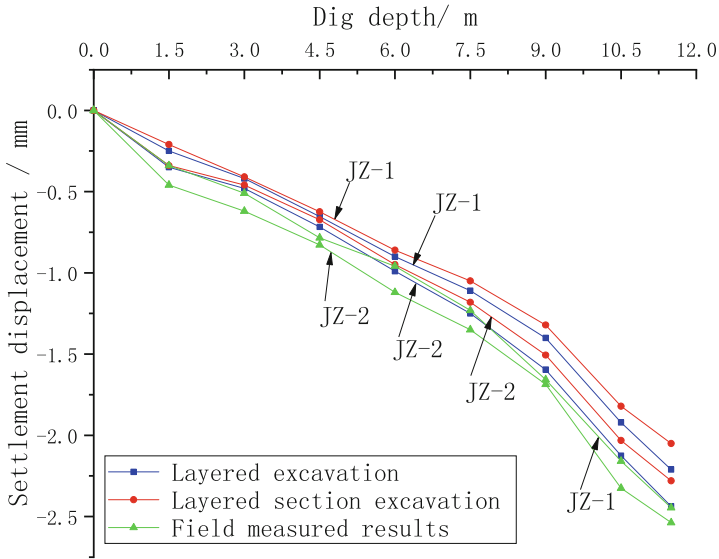**Fig. 11.** Building settlement displacement.

Fig. 12. The relationship between foundation settlement and excavation depth.

5.3 Influence of Deep Foundation Pit Excavation on Tunnel and Surface

5.3.1 Influence on Tunnel Deformation

In order to analyze the effect of deep foundation excavation on the deformation of metro tunnels, Fig. 13 shows the horizontal and vertical displacement diagrams of the tunnel after all the deep foundation pit excavation under two different types of excavation.

As can be seen from Fig. 13, the impact of deep foundation excavation on the overall deformation of the tunnel is not significant for either excavation method. In the vertical direction, the excavation of deep foundation pit causes downward displacement in the top area of the tunnel and upward displacement in the bottom area, which makes the tunnel flatten, but the displacement is relatively small. The upper and lower displacement difference caused by the two excavation methods does not exceed 0.5 mm, that is, the deformation of the tunnel in the vertical direction does not exceed 0.5 mm; In the horizontal direction, the excavation of deep foundation pit has caused the displacement to the West on the left and right sides of the tunnel, and the displacement is basically the same. It can be seen that the tunnel has basically no deformation in the horizontal direction.

5.3.2 Influence on Tunnel Displacement

To analyze the effect of deep foundation excavation on settlement and horizontal displacement in metro tunnels, Fig. 14 and Fig. 15 show the tunnel settlement displacement curve and horizontal displacement curve after all deep foundation pit excavation.

The displacement curve shows that the maximum settlement displacement at the top of the tunnel is 0.262 mm in the layered excavation method and 0.256 mm in the layered section excavation method, while the vertical settlement displacement of the whole
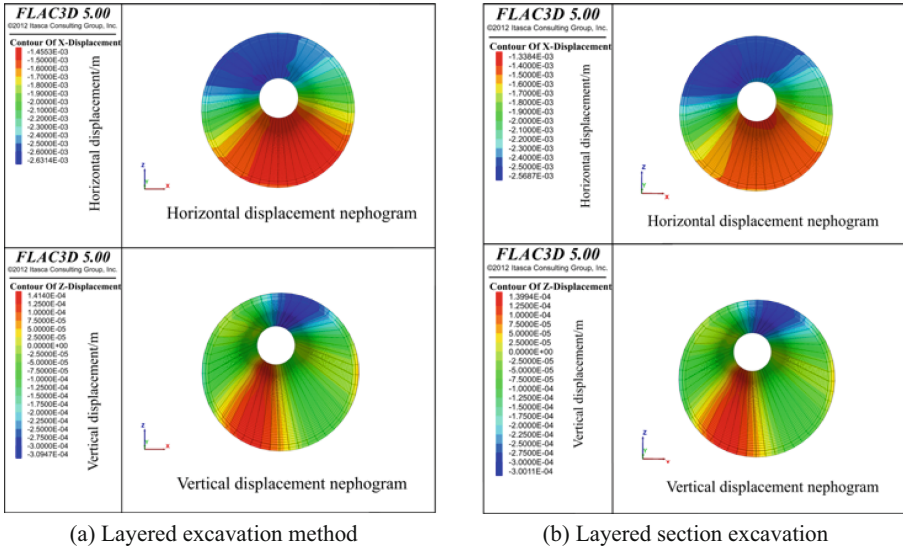
(a) Layered excavation method   (b) Layered section excavation

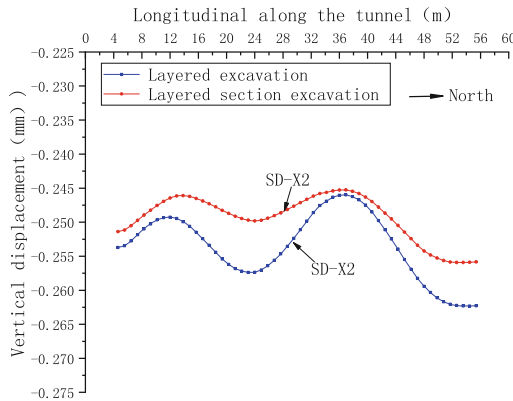**Fig. 13.** Deformation of tunnel under two different excavation methods

Fig. 14. The settlement displacement curve of tunnel Building settlement displacement.

tunnel is less than 0.3 mm, which means that the deep foundation excavation has a small effect on the settlement of the tunnel; However, deep foundation excavation has a greater impact on the horizontal displacement of the tunnel. As can be seen from the graphs, the horizontal displacement of the tunnel towards the deep foundation pit was generated in both excavation methods, with a maximum horizontal displacement of 2.03 mm in the layered excavation and 2.01 mm in the layered section excavation. Whether it is settlement displacement or horizontal displacement, the displacement under layered excavation is greater than that under layered section excavation, but the difference is small. It can be obtained that the different excavation methods of the deep foundation pit have less influence on the displacement of the tunnel.
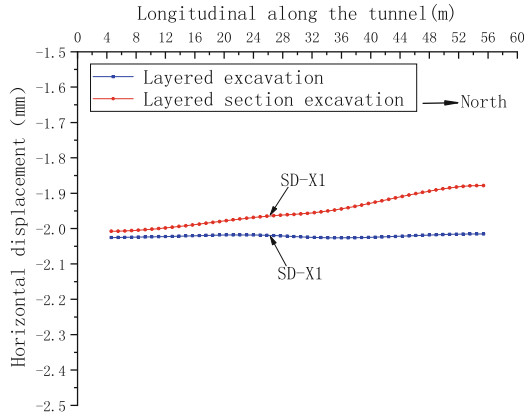
Fig. 15. The horizontal displacement curve of tunnel.

5.3.3 Impact on Surface Settlement Above Tunnel

Settlement displacement curves for the surface survey line on the east side of the deep foundation pit after excavation are shown in Fig. 16, and surface settlement curves with increasing excavation depth are shown in Fig. 17. The analysis shows that the surface settlement displacements near the boundary of the deep foundation pit are the largest, exceeding 3.5 mm for both excavation methods, whether the excavation is carried out in layers or in layers sections. When the surface is far away from the deep foundation pit, the settlement shows a decreasing trend. A peak in settlement displacement occurs at a distance of 16 m from the boundary of the deep foundation pit, directly below the tunnel. It can be concluded that the presence of the tunnel still has some influence on the ground settlement. The surface settlement caused by layered excavation is greater than that caused by layered and section excavation. As the excavation depth increases, the
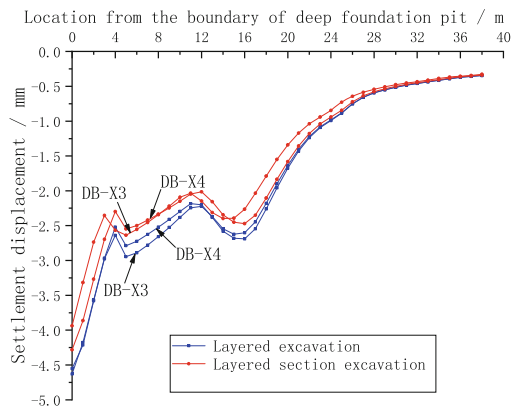

Fig. 16. The surface settlement displacement curve

difference between the two becomes more obvious. Once again, it is verified that the layered section excavation method has less influence on the deformation and displacement of the deep foundation pit and the surrounding buildings and tunnels.
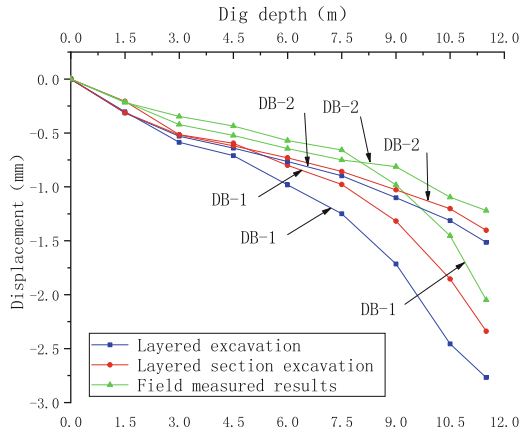

Fig. 17. Relationship between surface subsidence and excavation depth.

6 Conclusion

Taking a deep foundation pit in Shiliuzhuang, Beijing as the engineering background, FLAC3D was used to establish a numerical model of deep foundation pit excavation in a complex environment, and a numerical simulation study of deep foundation pit excavation under the conditions of different excavation methods was carried out to reveal the mechanism of the impact of different excavation methods on the safety of deep foundation pit on its surrounding tunnels and buildings, with the following main conclusions:

- The greater the excavation depth of the deep foundation pit in both excavation methods, the greater the horizontal displacement of the support structure on both sides. When the excavation depth is not large, the excavation method has no obvious influence on the horizontal displacement caused by excavation, but as the depth increases, at a certain value, the horizontal displacement under the layered excavation method starts to be larger than the horizontal displacement under the layered section excavation method. And the difference is more obvious as the depth deepens. It is easy to conclude that the layered excavation method is suitable for deep pits with shallow excavation depths, while layered section excavation method is suitable for deep pits with deep excavation depths. The reinforcement effect of the anchor cables reduces the effect of the excavation method on the deformation of the deep foundation pit. The surrounding buildings have a greater influence on the deformation of the deep foundation pit, but the influence of the buildings on the deformation of the deep foundation pit is less

than the effect of the prestressing anchor cable on limiting the deformation of the deep foundation pit layered section excavation.

- The excavation of deep foundation pit causes the settlement of adjacent buildings and surrounding surface. As the distance to the deep foundation pit increases, the settlement displacement of the building gradually increases and the surface settlement displacement gradually decreases. Different excavation methods have a great impact on the settlement of buildings and surrounding surface. The overall settlement displacement of buildings and surface under the layered section excavation method is less than that under the layered excavation. The closer to the deep foundation the more pronounced this phenomenon becomes. Compared with the layered excavation method, the layered section excavation method has less and safer impact on the settlement displacement of buildings and surface.
- The deep foundation excavation has a small effect on the settlement of the tunnel and a large effect on the horizontal displacement of the tunnel. Different excavation methods have little impact on the displacement of the tunnel. Whether it is the settlement displacement or horizontal displacement of the tunnel, the displacement under the layered excavation method is greater than that under the layered section excavation method, but the difference is small. The deep foundation excavation did not have a significant impact on the overall deformation of the tunnel.
- Deep foundation excavation will cause large settlement of the surface above the tunnel. Maximum ground settlement displacement near the boundary of the deep foundation pit. When the surface is far away from the deep foundation pit, the settlement shows a gradual decreasing trend. There is a peak value of increasing settlement displacement directly above the tunnel. The surface settlement caused by layered excavation is greater than that caused by layered section excavation.

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