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Influence of foundation pit excavation on deformation of subway tunnel below

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Abstract—**Aiming at the problem that the change of stress field caused by the excavation of a foundation pit in Zhengzhou drives the vertical and horizontal displacement and deformation of the subway tunnel which has been put into operation. In this paper, ABAQUS finite element software is used to conduct three-dimensional numerical simulation of foundation pit excavation, and the influence of the same foundation pit area but different length and width and the distance between the tunnel and the center of the foundation pit on the tunnel is discussed, and the size of the bending moment of the single tunnel under the foundation pit is analyzed during the excavation process. The results show that the excavation of the pit with four equal sides has the greatest effect on the vertical displacement of the tunnel below, which increases by 19.90% compared to the original pit shape displacement, and the vertical displacement of the tunnel increases by 14.58% compared to the original pit for the excavation of the pit with long sides parallel to the tunnel. When the horizontal distance of the tunnel from the center of the pit increases in sequence, the vertical displacement of the top of the tunnel will gradually decrease, and when the horizontal distance is 28m, the vertical displacement of the tunnel is 6.56mm. During the excavation of the pit, a pressure and tension area will appear in the tunnel section near the bottom of the enclosure structure, and this area will approach the center of the pit as the excavation depth deepens. The research results provide reference significance to the protection of the subway tunnel below the foundation pit during the excavation of the foundation pit under the geological conditions in Zhengzhou area, and accumulate experience for the construction of the project around the tunnel in Zhengzhou area.**

Keywords-component; excavation of foundation pit; numerical simulation; subway tunnel; displacement deformation

I. INTRODUCTION

With the stable and healthy development of China's economy, the increasingly developed transportation network in the country's major central cities, and the increasing utilization of underground space [1], it is inevitable that new foundation pits will be built too close to existing subway tunnels. Excavation of the foundation pit will cause changes in the displacement and stress fields of the surrounding soil, thus causing stress deformation in the tunnel below the pit [2, 3]. The response of the existing subway tunnel lining pipe sheet to the displacement of the surrounding soil is high, and the excessive soil displacement will cause damage to the continuity of the pipe sheet and a series of undesirable phenomena such as pipe sheet breakage and water seepage, which will further induce deformation and even straight damage in the subway tunnel [4, 5, 6]. Therefore, the safety and stability of the tunnel during the excavation of the foundation pit need to be analyzed and evaluated.

Many scholars have mainly used theoretical analysis and numerical simulation to study this research area of the effect of foundation excavation on subway tunnels. In terms of theoretical studies, most of the current scholars use a two-stage analysis, i.e., the additional load on the tunnel is calculated first and then the tunnel is considered as a Winkler elastic foundation beam to calculate the longitudinal displacement. Jiang et al [7] considered the stresses on the pit wall during the unloading process of the pit and proposed to use the Mindlin solution to calculate the additional stresses generated on the pit wall while solving for the longitudinal displacements of the tunnel. Chen et al [8] used the Mindlin elastic half-space stress solution to quantitatively solve the additional stresses and bulges in the tunnel structure during the unloading of the pit, taking the actual project as an example. Zhou et al [9] established the differential equations for a double-bore tunnel under additional loads in the context of a real project and further corrected the accuracy of the foundation parameters.

In terms of numerical analysis, Based on an actual project in Shanghai, Huang et al [10] simulated the response of foundation pit excavation on the tunnel beneath under four different working conditions, such as soil reinforcement and pit bottom stacking load. The results pointed out that the impact range of pit excavation on the underlying tunnel is roughly six times the width of the pit, and a reasonable tunnel protection scheme should be developed. Wang et al [11] used numerical simulation to analyze the effect of foundation pit unloading on the downward lying tunnel. The conclusion shows that the specific manifestation of tunnel deformation is vertical upward movement, and proposes protective measures such as reinforcement of the soil around the tunnel when designing the foundation pit project. Yao et al [12] studied the strain law of the tunnel by unloading-loading of the pit excavation through indoor tests and numerical simulation, and analyzed the distance of the pit bottom from the top of the tunnel and the effect of pit loading on the tunnel.

In this paper, a three-dimensional model of the foundation pit excavation process is established to analyze the influence of influencing factors such as the shape of the pit and the distance of the tunnel from the center of the pit on the displacement and bending moment of the tunnel below, taking a foundation pit of Line 1 of the Zhengzhou subway as an example. The action law is discussed, which can provide a reference for similar projects and accumulate experience for tunnel research in Zhengzhou area.

II. ENGINEERING BACKGROUND

A. Foundation Pit Overview

The pit project is located in the busy area of Zhengzhou City, surrounded by several buildings, and two tunnels of Metro Line 1 that have been put into operation below the foundation pit. The shape of the foundation pit excavation can be approximately equivalent to a rectangle with a length of 20m and a width of 45m, and the excavation depth is 8m, and the form of layered excavation is used. The diameter of both tunnels directly below the pit is 6m, the horizontal spacing of the tunnels is 13m, and the vertical distance between the center of the longitudinal surface of the tunnels and the bottom of the pit is about 12m. The relative positions of the foundation pit and the existing tunnel below are shown in Fig. 1 below.

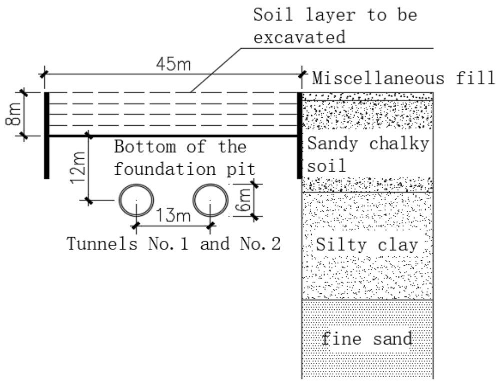

Fig 1. Relative position of the foundation pit and the tunnel below

B. Geological Conditions

According to the actual survey report of the project, the soil layers involved in the scope of study and analysis can be roughly divided into (1) miscellaneous fill with a thickness of 1.5m, (2) Sandy chalky soil with a thickness of 17m, (3) Silty clay with a thickness of 20m, and (4) fine sand with a thickness of 30m, and the specific physical parameters of each soil layer are shown in Table. 1.

Table 1. Parameters of physical properties of soil layers

Soil layers	Density (kN/m^3)	Modulus of elastic (MPa)	Internal Friction angle (°)	Cohesion (kPa)	Poisson's ratio
miscellaneous fill	17.8	25	24	19.6	0.3
Sandy chalky soil	19.6	27	24	20	0.31
Silty clay	19.8	30	31.6	22	0.3
Fine sand	21	40	35.6	0	0.3

C. Enclosure Structure

The foundation pit enclosure structure is in the form of supporting piles and underground diaphragm walls combined with steel supports. The supporting piles are composed of SMW method piles with a diameter of 850mm, an embedding depth of 16m and a pile center spacing of 600mm. Steel support along the excavation direction in three layers, steel support specifications are Φ800mm × 16mm, the horizontal spacing of 5m, each vertical spacing of 2m, the first layer of steel support from the pit excavation surface for 1m.

III. NUMERICAL MODELING PROCESS

A. Selection of the Constitutive Model and Component Parameters

In order to facilitate the calculation, the model makes the following assumptions: (1) ignore the axial pressure problem by the pit precipitation, (2) ignore the time effect and soil consolidation creep generated during excavation, (3) the same physical properties of the soil is assumed to be an isotropic elastic-plastic body, (4) the lining structure and the soil are coherently deformed. The soil constitutive relationship adopts the Mohr-Coulomb constitutive model, and soil damage occurs when (1) equation is satisfied.

$$\frac{1}{2}(\sigma_1-\sigma_3)=\left[c\cdot ctg\varphi+\frac{1}{2}(\sigma_1+\sigma_3)\right]\sin\varphi \tag{1}$$

In equation (1): σ_1 denotes the maximum principal stress, σ_3 denotes the minimum principal stress, c denotes the cohesive force, φ denotes the angle of internal friction.

A calculation unit of enclosure structure is selected, and the supporting pile is equivalent to the underground diaphragm wall according to the principle of the same stiffness, moment of inertia and bending stiffness, namely, equation (2), so that the moment of inertia of the Shadowed part in Fig. 2. after equivalence is equal to the moment of inertia of the underground diaphragm wall. The width of the equivalent diaphragm wall is 800mm, and the specific parameters of the diaphragm wall and steel support are shown in Table. 2 below.

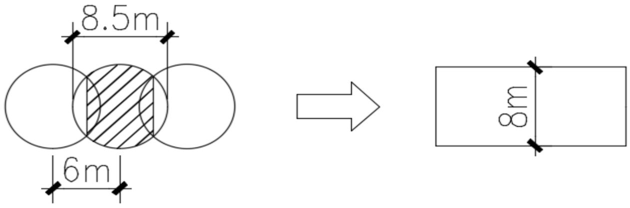

Fig 2. Computational unit equivalence

$$E_w I_w = E_p I_p \tag{2}$$

In equation (2): E_w denotes the elastic modulus of diaphragm wall, I_w denotes the moment of inertia of diaphragm wall section, E_p denotes the elastic modulus of supporting pile, I_p denotes the moment of inertia of supporting pile.

Table 2. Physical parameters of enclosure structure

Name	Density (kN/m^3)	Elastic modulus(MPa)	Poisson's ratio
Underground diaphragm wall	22.54	34500	0.2
Steel support	78.5	206000	0.2

The tunnel lining is simplified as an orthotropic barrel structure, and its transverse and longitudinal stiffness reduction coefficients are taken as 0.7 and 0.186. According to the elastic theory formula:

$$\{\sigma\} = [D]\{\varepsilon\} \tag{3}$$

Assuming that the elasticity matrix [D] is symmetric

$$\begin{aligned} \nu_{xy} / E_x &= \nu_{yx} / E_y \\ \nu_{xz} / E_x &= \nu_{zx} / E_z \\ \nu_{yz} / E_y &= \nu_{zy} / E_z \end{aligned} \tag{4}$$

In Equation 4: x, y, and z are the three main directions of the orthogonal anisotropy of the material, and the transverse and longitudinal stiffnesses of the equivalent barrel structure are 24 GPa and 6.4 Gpa, respectively.

B. Model Meshing and Boundary Condition Setting

The horizontal influence of the excavation of the foundation pit on the surrounding soil is about 3 to 4 times the depth of excavation, and the influence range below the bottom of the foundation pit is about 2 to 2.5 times the depth of excavation. The length and width of the model are 120 m and the height is 40m. C3D8R solid cells are selected as the grid type for the soil, lining structure and ground connection wall, with a total number of 114260 cells, and beam linear beam cells are selected for the steel support, with a total of 240 cells. The displacement constraints in X and Y directions of X and Y boundaries of the model are fixed, and the displacements in X, Y and Z directions of Z boundaries at the bottom of the model are fixed. The specific diagram of the model is shown in Fig. 3.

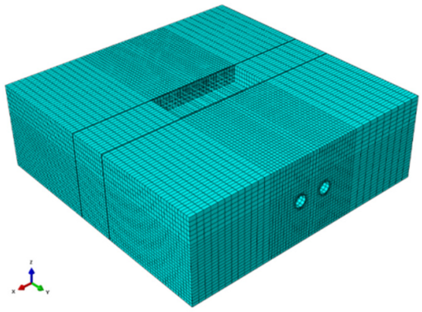

Fig 3. Mesh of finite element mode

C. Working Condition Simulation

As shown in Table. 3, working condition 1 is the real condition and working condition 2 is the simulated condition to simulate the impact of foundation pit excavation on the single tunnel below. The support conditions, tunnel diameter, and distance from the top of the tunnel to the bottom of the pit in working condition 2 are the same as those in working condition 1, and the rest of the working conditions are changed one by one on the basis of working condition 2.

Table 3. Simulation of different working conditions

working condition	Content (excavation depth of the pit is 8m, in accordance with the 2m depth of excavation step by step)
1 (Real working condition)	Foundation pit length 20m, width 45m
2 (Single tunnel below the foundation pit)	Foundation pit length 20m, width 45m
3 (Change of excavation size)	Foundation pit length 45m, width 20m
4 (Change of excavation size)	Foundation pit length 30m, width 30m
5 (Change horizontal distance)	The horizontal distance between the center point of the tunnel section and the center point of the foundation pit is taken as 7m
6(Change horizontal distance)	The horizontal distance between the center point of the tunnel section and the center point of the foundation pit is taken as 14m
7 (Change horizontal distance))	The horizontal distance between the center point of the tunnel section and the center point of the foundation pit is taken as 21m
8 (Change horizontal distance)	The horizontal distance between the center point of the tunnel section and the center point of the foundation pit is taken as 28m

IV. Analysis of Simulation Results

A. Tunnel Deformation

As shown in Fig. 4, the vertical displacement vector cloud of the tunnel after the completion of the excavation of the foundation pit in working condition 1, it can be seen from the figure that the whole vertical displacement value of the tunnel gradually decreases from the midpoint to both sides, and the two tunnel displacement deformation law is basically the same. The maximum displacement is 14.08mm, which occurs at the top of the midpoint of the tunnel, and the minimum vertical displacement at the bottom of the tunnel is 0.72mm.

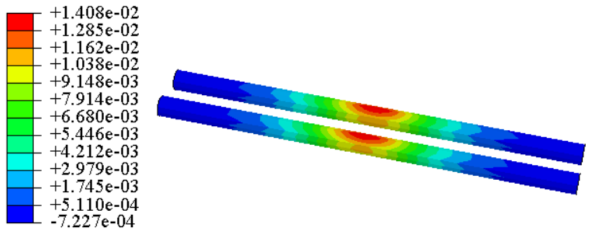

Fig 4. Vertical displacement of tunnel(unit: m)

Given that the displacement and deformation rules of tunnel No.1 and No.2 are basically the same, tunnel No.1 is taken as an example to analyze the vertical displacement of its top during the excavation of the foundation pit.

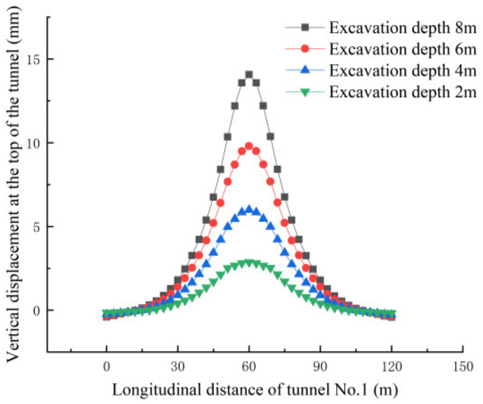

Fig 5. Vertical displacement at the top of tunnel No.1

As shown in Fig. 5, the vertical displacement at the top of the tunnel basically shows a Gaussian distribution, when the excavation depth is 2m, the maximum vertical displacement at the top of the tunnel is 2.86mm, and as the excavation depth becomes larger, the tunnel displacement increases until the tunnel vertical displacement reaches 14.07mm when the excavation is completed. It can be seen that the excavation depth is positively correlated with the vertical displacement of the tunnel. With the increase of excavation depth, the change of tunnel displacement is gradually accelerated. The fastest change of vertical displacement at the top of the tunnel is located at the excavation boundary, i.e., about 10m from the left and right sides of the tunnel midpoint, and when the excavation depth is 2 and 4m, the fastest change of displacement occurs at 2m from the outside of the pit boundary, with displacement increases of 0.41mm and 0.79mm respectively, while when the excavation depth is 6 and 8m, the fastest change of displacement occurs at the pit boundary, with displacement increases of 1.27mm and 2.04mm respectively. It can be seen that the point with the fastest change in displacement amplitude will keep approaching the midpoint of the pit as the excavation depth increases.

As shown in Fig. 6, the nodes are numbered for the tunnel section located at the center of the pit. From Fig. 7 and Fig. 8, it can be seen that the horizontal displacement of tunnel increases continuously during the excavation of the foundation pit until it reaches the maximum when the excavation of the foundation pit is completed. The maximum value of horizontal displacement of tunnel No.1 is 3.95mm, which is located in node 10, and the maximum value of horizontal displacement of tunnel No.2 is 3.90mm, which is located in node 4.

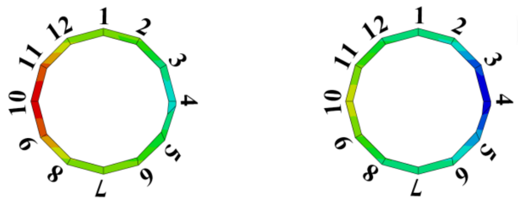

Fig 6. Node number of tunnel section 1 and 2 at the center of the foundation pit

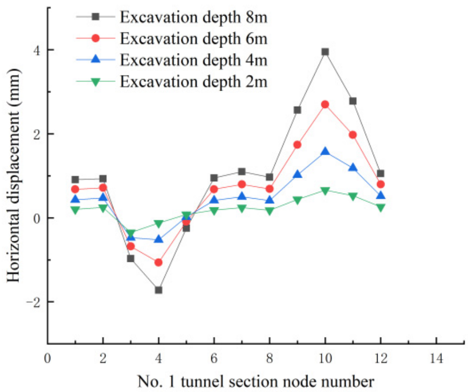

Fig 7. Horizontal displacement of tunnel section No.1

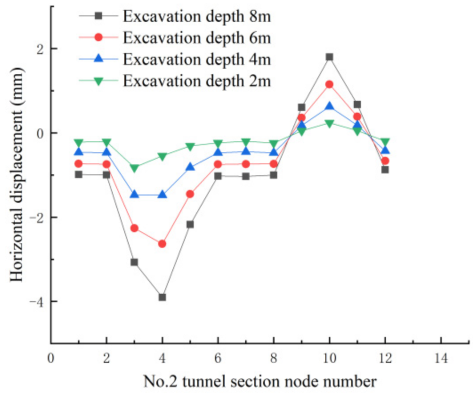

Fig 8. Horizontal displacement of tunnel section No.2

B. Influence of Different Excavation Sizes of the Foundation Pit on the Tunnel

Tunnel deformation will increase with the depth of excavation, as shown in Fig. 9 for the same area but with different lengths and widths for the effect of pit excavation on the displacement of the top of the tunnel. From the figure, it can be seen that working condition 4 has the greatest effect on the displacement of the top of the tunnel, with the vertical displacement value reaching 17.59mm, which increases by 19.90% compared to working condition 2.

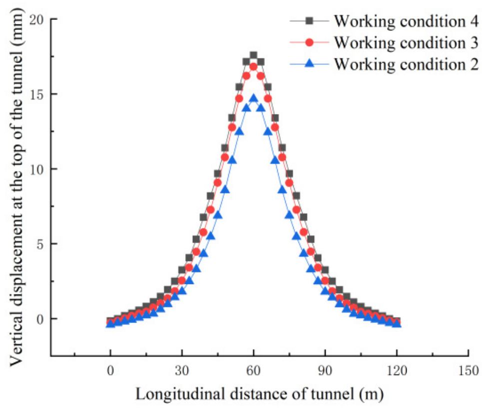

Fig 9. Vertical displacement of the top of the tunnel under different pit excavation dimensions

Fig. 10 shows the horizontal displacement of the tunnel section located at the center of the pit, and the node setting is the same as Fig. 5. As all three working conditions are single tunnel below the pit, the horizontal displacement is no longer affected by the adjacent tunnel, and the overall graph is centrosymmetry, while different from the vertical displacement, the horizontal displacement of working condition 3 is the largest, and the maximum displacement value is 5.63mm.

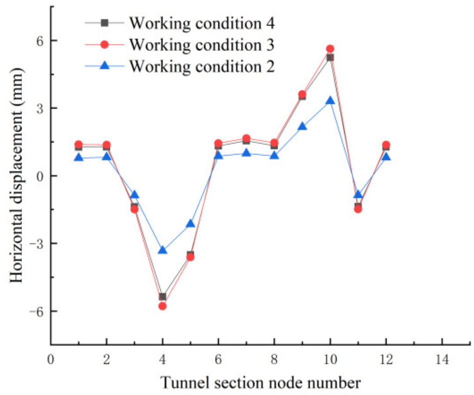

Fig 10. Horizontal displacement of the tunnel section at the center of the pit under different pit excavation dimensions

C. The Effect of Horizontal Distance Changes on the Tunnel

As shown in Fig. 11, the maximum horizontal and displacement of the tunnel under working conditions 2, 5, 6, 7 and 8, it can be seen that when the horizontal distance between the tunnel and the pit varies, the effect of the pit excavation on the vertical displacement of the tunnel is much larger than the horizontal displacement. The vertical displacement value of the top of the tunnel in working conditions 2 was the largest, reaching 14.67mm, and the displacement value in working conditions 4 was reduced by 55.28% compared to that in working condition 2. With the increase of the horizontal distance of the tunnel from the pit, the maximum horizontal displacement of the tunnel showed a trend of increasing first and then decreasing. When the distance was 14m, the horizontal displacement of the tunnel reached the maximum value of 5.05mm, and then showed a trend of gradually decreasing due to the existence of the pit enclosure structure.

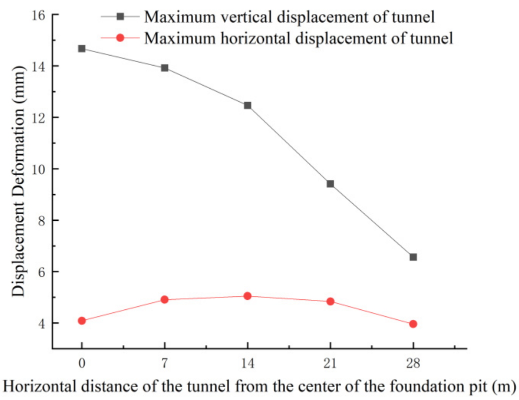

Fig 11. Tunnel displacement at different horizontal distances between tunnel and foundation pit

D. Tunnel Bending Moment

As shown in Fig. 12, the bending moment in tunnel No. 1 for working condition 1. The rate of change of the bending moment value at the bottom of the tunnel is much greater than that at the top outside the pit excavation range, while the two are reversed within the pit completion range. The bending moment at the top of the tunnel tends to smooth out overall outside the excavation area of the pit, between about 38m to 47m and 72m to 81m, and the bending moment at the top of the tunnel will gradually increase. The bending moment at the bottom of the tunnel reaches its maximum value at both ends of the tunnel, and then decreases when the distance between the tunnel section and the center of the pit decreases, reaching a minimum value at about 47m and 81m, after which the bending moment changes in a "wave-like" pattern.

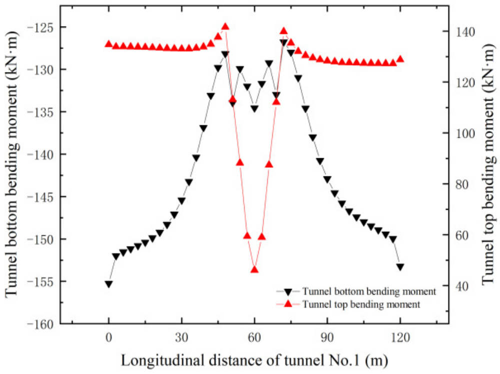

Fig 12. Bending moment value at the bottom and top of Tunnel No. 1

When the excavation of the foundation pit was completed, the tunnel showed a bending moment distribution shape as shown in Fig. 13 (taking Tunnel 1 as an example) at a location about 6m from the center of the pit at both ends. Fig. 14 shows the bending moment force in this shape. The maximum stress point of the bending moment appears at the position of 52.5m and 67.5m of the tunnel, and the two points are subjected to tension and compression at the same time, and the magnitude of the bending moment is basically the same.

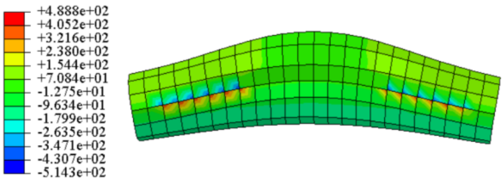

Fig 13. Local bending moment of tunnel No.1(unit: kN·m)

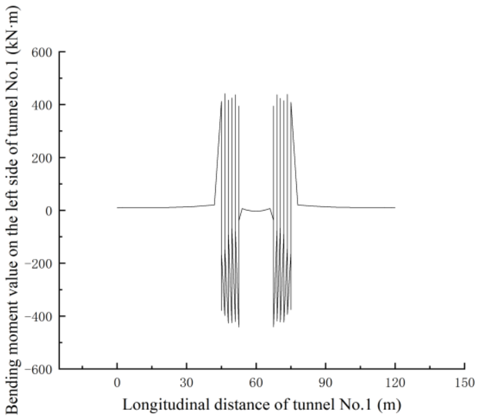

Fig 14. Bending moment value on the left side of tunnel No.1

V. CONCLUSIONS

By considering the interaction between the pit, the soil and the subway tunnel, a three-dimensional model was established to analyze the response law of the tunnel below the pit during the excavation of the pit, and the conclusions are obtained as below:

1. The excavation of the foundation pit caused the original stress field of the soil to change, and the soil above the tunnel below showed an overall upward displacement trend due to the unloading effect. The displacement value at the top of the tunnel is the largest, and the displacement value at the bottom is the smallest, with a difference of 13.36mm between the two displacement values.

2. Pit excavation has a much greater effect on the vertical displacement of the tunnel below than the horizontal displacement. The four equal sides of the pit excavation have the greatest effect on the vertical displacement of the tunnel compared to the other two types of pits. The farther the tunnel is from the center of the pit, the weaker the effect of the pit excavation on it. When designing the foundation pit, try to choose a design solution where the short side of the pit is parallel to the tunnel.

3. Outside the excavation range, the bending moment at the top of the tunnel is smaller than that at the bottom, while within the excavation range, the former bending moment is larger than the latter. The bending moment on both sides of the tunnel is basically 0 outside the excavation range, and the tunnel sides are subject to both tension and pressure at the enclosure structure. During the excavation process, the bending moments on the sides of the tunnel are smaller than those on the top and bottom.

4. As the excavation depth of the pit increases, the maximum vertical displacement and the maximum horizontal displacement of the tunnel below also increases, and the relationship between them is approximately linear. Effective control measures should be taken in the actual project, otherwise the maximum vertical displacement of the tunnel will exceed the allowable value of tunnel deformation, and the tunnel lining structure will be damaged.

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