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Analysis on the influence of excavation close-range foundation pit on existing tunnel

LIU Chen yang[1, a], LIU Jun yan[1, 2, b], WU Yong zhen[3, c], LIU Yong[4, d]

[1] School of Civil Engineering and Architecture, University of Jinan, Jinan 250022, China

[2] The engineering technology research center for urban underground engineering supporting and risk monitoring of Shandong Province

[3] China Railway NO.3 Engineering Group Co., Ltd.The Fifth Engineering Co., Ltd

[4] Ji'nan Ding Hui Civil Engineering Technology Co., Ltd

[a]liuchenyang919@163.com, [b] liujunyan@vip.sina.com, [c] jidigaofei@163.com,

[d] lydinghui@163.com

Abstract. The development of underground space has resulted in a number of neighboring excavation projects, especially the excavation of the foundation pit that span existing subway tunnels. While facing the risk of excavation of the foundation pit crossing tunnel are not only faced with the risks of itself, but also the safety of the existing tunnel is always the serious and difficult problems in the engineering field. This paper takes the foundation pit project of the existing subway tunnel of Jinan as the background. The minimum distance between the pit bottom of the access line and the tunnel is only 1.8m, and the direction of the foundation pit is 15°from the tunnel, it’s close to parallel. Unloading of foundation pit is boned to cause the deformation of inferior tunnel. In order to study the influence of the existing tunnel, we carry out numerical simulation by the finite element software Midas GTS/NX to study the displacement field and stress field of tunnel under the condition of excavation of foundation pit. We study the measures of reinforcement based on the results and further analyse the results of reinforcement. At the same time, we combine an site monitoring data to confirm the effect of reinforcement. Preliminary analyses shows that the excavation of foundation pit has little influence on the horizontal displacement of tunnel and has great influence on vertical displacement. Without reinforcement measures, the uplift of the tunnel reaches 23.11 mm, which exceeds the requirement of deformation control. By grouting the soil between the foundation pit and the tunnel and loading it at the bottom of the tunnel, the uplift of the tunnel is reduced to 4.86 mm, which is consistent with the field measured data, and the reinforcement effect is remarkable. In order to reduce the safety risk, it is necessary to take relevant protection measures in similar projects.

1. Introduction

According to statistics, as of December 31, 2017, the total length of subway lines in China has reached 3894.2 km, and China has become the largest urban rail transit construction market in the world [1]. The underground space is becoming "congested", there are many adjacent excavation projects around the subway tunnel. The excavation unloading is bound to cause the change of the stress field and displacement field of the subway tunnel, which causes the additional internal force and deformation of the tunnel structure, and seriously threatens the safety of the subway, Burford[2] first reported the engineering case of tunnel excavation over 27 years' cumulative uplift 50mm above the subway tunnel; Chang[3] and so on analyzed the damage of the tunnel structure caused by a subway tunnel in Taipei due to the excavation of the adjacent foundation pit. So it is very important to understand the deformation characteristics and internal force distribution of existing subway tunnel during excavation[4].

For the deformation of existing tunnels caused by excavation,many experts and scholars have carried out a lot of research work. Zhang Junfeng et al. [5]used Boussinesq solution to analyze soil deformation caused by excavation unloading of foundation pits,considered the space-time effect of soft soil deformation and proposed a calculation method for predicting tunnel uplift volume;Huang Hongwei et al [6] combined with the foundation pit engineering of the Shanghai Bund, adopted the finite element software PLAXIS-GID for numerical simulation and analyzed the tunnel deformation law under different reinforcement measures. The above research results mainly take the typical soft soil area such as Shanghai as the engineering background, but the similar problems under other geological conditions are not enough. In this paper, based on the construction of the close pit excavation above the subway tunnel, the deformation law of the tunnel under typical excavation conditions is studied, and the control effect of the reinforcement measures is analyzed. At the same time, the reinforcement effect is verified through the data of field monitoring.

2. Background

The total length of an entrance/exit line at R3 line of Jinan rail transit is 1033.5m, and the depth of the foundation pit is 3.8~103.1m. At the bottom of the foundation pit is the subway shield tunnel completed in advance. The southern section of the pit crosses with the left line of the existing tunnel. The angle between the direction of the foundation pit and the tunnel is 15°, and the minimum distance from the bottom of the tunnel to the tunnel is only 1.8m. The project is located in the landform area of low hills and hills and the strata from top to bottom involve 1-1 prime fill, 17-1 gravel soil and 21- 2 weathered limestone. The depth of foundation pit excavation is about 9.4m, and the width is about 12.85m. Slope and anchor are selected for supporting. The slope rate is 1:0.5. The length of the anchor is 5m~8m, the horizontal distance is 1.5m, vertical distance is 2m.The plane position of foundation pit and subway tunnel is shown in figure 2-1, and the position of section is shown in figure 2-2. The main physical and mechanical parameters of the formation are shown in Tab.2-1.

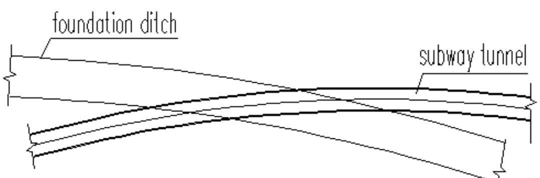

Fig. 2-1 Plane position relation diagram

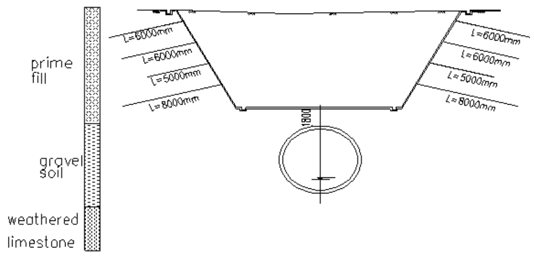

Fig.2-2 Profile position relation diagram

Tab. 2-1 Formation parameter value

Serial number	Item	Thickness（m）	Bulk density γ(kN/m3)	Compression modulus Es (MPa)	Poisson ratio υ	Cohesive forcec(kPa)	Internal friction angle φk(°)
1	Prime fill (1-1)	11	18.9	-	-	26	16.3
2	Gravel soil(17-1)	7.9	21.0	4.8	0.18#	27	15
3	Weathered limestone (21-2)	17.5	26.9	7.5	0.21#	48	20

(Notice：“#” Indicates that the value takes empirical value.)

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3. Analysis of deformation mechanism of bottom tunnel caused by excavation of foundation pit

Before the excavation of foundation pit, the interaction between the bottom tunnel and the surrounding soil has become stable, and the tunnel is in the state of force balance, which is shown in figure 3-1(a). With the excavation of the foundation pit above the tunnel, the displacement field and internal force field of the original soil will change, and the stratum loss will be transmitted to the tunnel. It is shown that vertical unloading causes the upward rebound of the soil beneath the bottom of the pit and the uplift deformation of the lower tunnel due to the decrease of overlying soil pressure. The horizontal stress on both sides of the horizontal tunnel is increased by the squeezing action of the soil. The influence of excavation unloading on the overlying earth pressure of the tunnel is reduced, and the cross section of the tunnel presents a vertical ellipsoid of "horizontal compression and vertical stretching", as shown in figure 3-1(b).

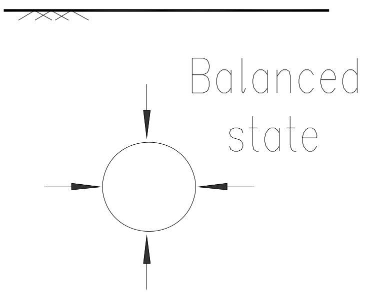


Fig. 3-1(a) Stress balance state before excavation

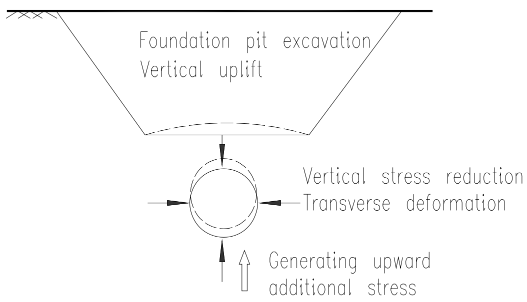
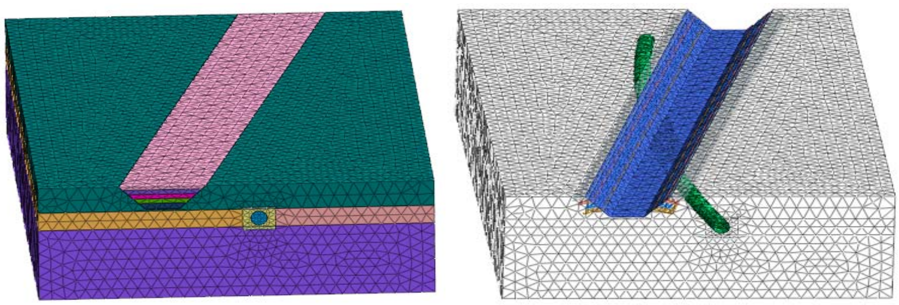


Fig. 3-1(b) Stress imbalance after excavation

4. Numerical analysis

4.1. calculation model and basic assumption

In this paper, the finite element software Midas GTS/NX is used to expand the numerical analysis. The size of the model is: length * width * height= 250m * 150m * 50m. The computational model is shown in figure 4-1. Horizontal and vertical displacement constraints are applied at the bottom of the model, horizontal displacement constraints are adopted in the lateral direction, and the surface of the upper surface is set as a free surface without any constraints.



(a) Before excavation of foundation pit (b)After excavation of foundation pit

Fig. 4-1 Numerical model

For the convenience of calculation, the following assumptions are made in the analysis:

(1) The solid element is used to simulate the soil, the embedded truss is used to simulate the bolt, and the plate element of the tunnel is simulated by the plate unit.All these agree with the assumption of the MohrCoulomb constitutive model.

(2) The same layer of soil is homogeneous and continuous, and has the isotropic.

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(3) The effect of groundwater is not considered.

4.2. Simulation of construction conditions
Before the foundation pit is excavated, the original in-situ stress and the simulation of the subway tunnel excavation are carried out. After the clearance is cleared, the excavation of the foundation pit above the tunnel is simulated. The excavation of the foundation pit is carried out according to the principle of "stratified excavation and supporting with excavation", that is, the first layer of soil excavation→the first anchor bolt→second layers of soil excavated→second anchor bolts→third layers of soil excavated→third rock bolts→fourth layers of soil→fourth road bolts.

4.3. numerical simulation results
Fig.4-2 and fig.4-2 are clouds of vertical displacement of foundation pit and tunnel after excavation. It can be seen from the diagram that the excavation of the foundation pit is affected by unloading after excavation, and the upwardly uplift of the bottom soil is produced, with the maximum uplift of 30.47mm, which is located at the crossing between the foundation pit and the tunnel. The existing tunnel under the foundation pit also produces uplift deformation, with the maximum uplift of 23.11 mm(The control value is 20mm, which does not meet the requirements of deformation control), which is located directly below the foundation pit. The analysis shows that the deformation of foundation pit and tunnel is consistent, and the maximum vertical displacement is located in the cross crossing section between them.

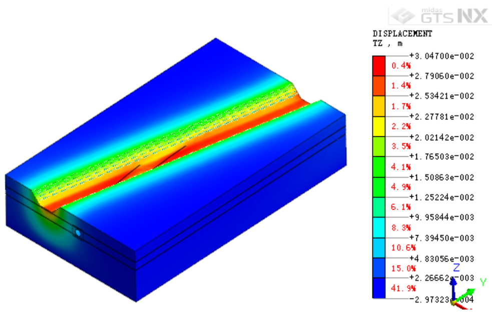


Fig. 4-2 Vertical displacement of the foundation pit

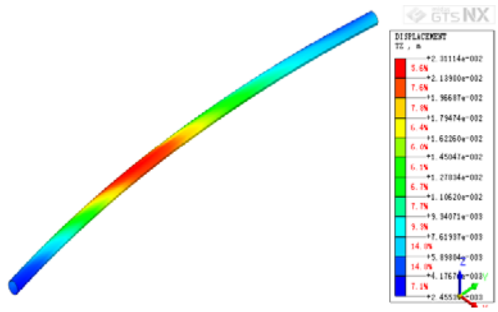


Fig.4-3 Vertical displacement cloud of the tunnel

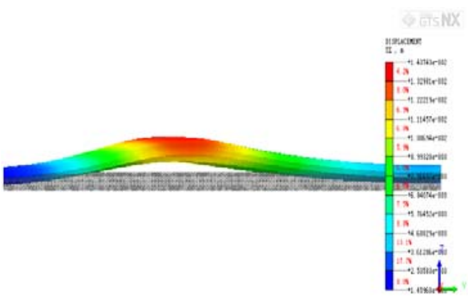


Fig.4-4Tunnel uplift deformation

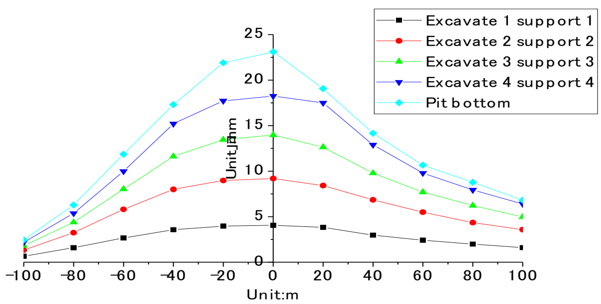


Fig.4-5Longitudinal uplift of tunnel in different stages of excavation

Fig.4-4 shows the comparison between before and after deformation of the tunnel and Fig.4-5 shows the tunnel vertical uplift changes diagram at different stages of foundation pit excavation. It can be seen from the diagram that with the increase of excavation depth, the uplift of the tunnel under the foundation pit increases gradually, and the maximum uplift is located directly below the foundation pit in the cross span section. Taking the location as the axis center, the uplift of the tunnel gradually decreases to both sides, and is approximately symmetrical about the axis. When the foundation pit is excavated to the bottom at the last step, the vertical displacement of the tunnel exceeds the control value.

4.4. *Study on reinforcement measures of Tunnel*

From the foregoing analysis, it can be seen that without reinforcement measures, the maximum amount of uplift in the tunnel is 23.11 mm, which does not meet the deformation control requirements of the 20 mm deformation of the Code for monitoring measurement of urban rail transit engineering(GB 50911-2013). In order to protect the safety of the existing tunnel beneath the foundation pit, the protection measures are adopted in the actual process, such as heap loading at the bottom of the tunnel and grouting reinforcement around the tunnel. The bottom load is 70KPa and grouting material is cement slurry. The cross section of the soil around the tunnel is shown in Fig. 4-6.

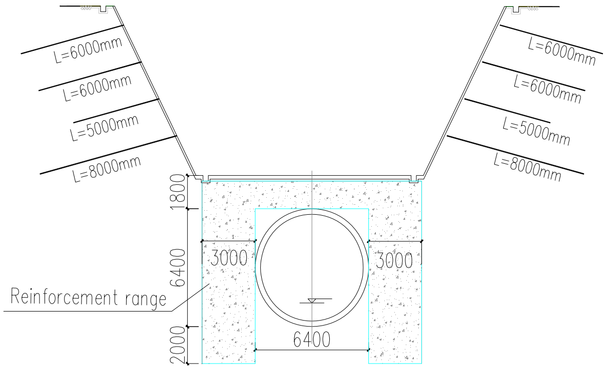
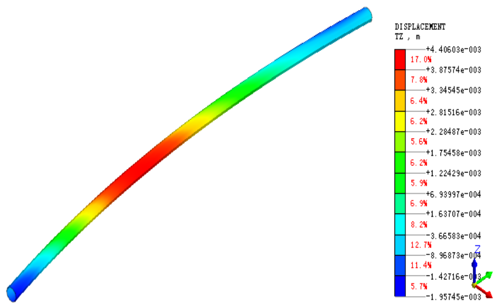


Fig. 4-6 Tunnel reinforcement section

Fig.4-7 shows the vertical displacement cloud diagram of the tunnel after taking protective measures. It can be seen from the figure that the maximum uplift of the tunnel is greatly reduced from 23.11mm to 4.86mm, which is located directly below the foundation pit at the crossover.



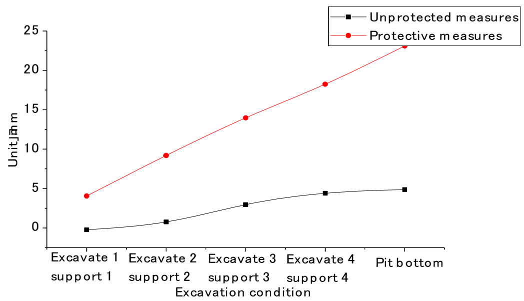


Fig.4-7 Vertical displacement cloud of the tunnel Fig.4-8 Vertical displacement of the tunnel

Fig.4-8 shows the comparison of the maximum vertical displacement of the tunnel after excavation with or without protective measures. It can be seen from the graph whether tunnel protection measures are taken or not, the trend of the tunnel uplift is roughly consistent in the excavation process. After the reinforcement scheme was adopted, the maximum uplift of the tunnel was reduced from the 14.37mm to 4.86 mm, and the protective effect was obvious, which can greatly reduce the safety risk of the subway tunnel in the construction process of the foundation pit.

5. Analysis of tunnel monitoring results during construction

In order to ensure the safety of the existing subway tunnel during the construction of foundation pit, key monitoring is carried out for the tunnel below the crossing. Fig.5-1 and 5-2 are the comparison of the measured data and numerical results of the vault settlement and the clearance convergence of the tunnel below the cross section. The analysis shows that the trend of the tunnel uplift remains fairly uniform. When the foundation pit is excavated to the bottom of the pit, the numerical calculation result of the tunnel dome settlement is 4.86 mm, and the actual field measurement result is 3.04 mm, with a small difference. The convergence results of both tunnels are relatively small, but the measured data are in a negative and changing state, and there is no obvious change rule, which is not consistent with the numerical results.

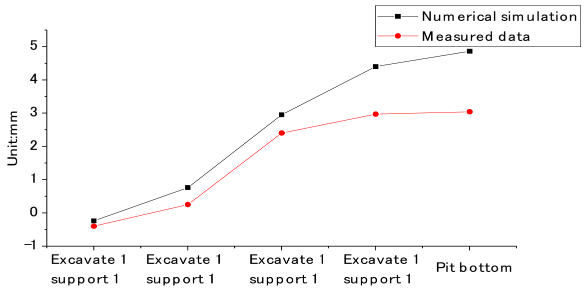


Fig.5-1 Tunnel dome settlement

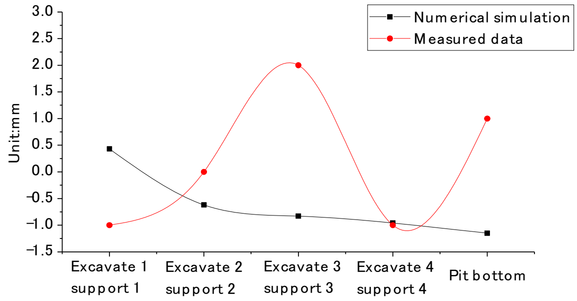


Fig.5-2 Tunnel clearance convergence

6. Conclusion

(1) The displacement field of the original soil is changed by the influence of the excavation of foundation pit. The displacement of the existing tunnel below the foundation pit is upward by the influence of its overall impact. And the largest displacement is located at the bottom of the foundation crossing the crossing section.

(2) Calculations show that in the process of construction of the foundation pit, protective measures such as loading at the bottom of the pit and grouting reinforcement of soil around the tunnel can effectively reduce the amount of tunnel uplift and greatly reduce the safety risk of the existing tunnel.

(3) Compared with the results of numerical simulation and measured data, the horizontal displacement of tunnel is small, and the excavation of foundation pit has little influence on it. The horizontal displacement data of tunnel is disorderly, and there is no obvious deformation rule.

(4) For complex geotechnical problems, numerical calculation can effectively predict the actual engineering deformation problems and provide some reference for field construction.

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