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Midas-GTS Three-dimensional Numerical Simulation Analysis of the Impact of Deep Excavation on Subway Safety Assessment

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Abstract: Taking the deep foundation pit project of a high-rise building near the subway as an example, this paper analyzes the engineering overview and geological conditions. Based on the subway safety protection and monitoring items and control indicators of the foundation pit project, Midas-GTS software is used to treat the deep foundation pit, surrounding soil, adjacent buildings, and subway engineering as a system, and establish a three-dimensional simulation model of the foundation pit. Complete the simulation of the step-by-step excavation construction process of the foundation pit, and conduct numerical simulation analysis to obtain the horizontal and vertical deformation cloud maps of the subway structure under different working conditions. It Summarizes the maximum vertical and horizontal displacement of the subway, and compare it with the actual monitoring results. The results show that the model established by Midas-GTS is reliable, and the subway safety meets the requirements. The model establishment method and analysis method provide data support for similar projects in the future.

Keywords: Midas-GTS; Complex Environment; Near the Subway Deep Foundation Pit; The Impact on the Surrounding Environment; Numerical Simulation Analysis

1. Introduction

At present, with the rapid development of urban subway engineering, subway lines have gradually spread all over the city's underground, and a series of commercial complexes have appeared near a large number of newly built subways, resulting in some deep and large foundation pit engineering. [1] Foundation pit is adjacent to the complex environment such as subway tunnels, urban roads and pipelines, river courses, etc. Therefore, the excavation of deep foundation pit is bound to have a certain impact on the surrounding environment, especially the subway tunnels, and the deformation requirements of the subway tunnels that have been operated are extremely strict. Therefore, under many circumstances, it is necessary to calculate and evaluate the impact of foundation pit construction on subway tunnels, and three-dimensional numerical simulation [2-9] has become an important means in this calculation field, in which Midas-GTS [10-14] shall be used to establish three-dimensional models, to solve complex engineering problems, which is gradually popularized.

Through the analysis of the horizontal and vertical displacements of soil in excavation of foundation pit and the horizontal and vertical displacements near the subway, and using Midas software to carry out numerical simulation analysis and actual monitoring comparative analysis, to provide certain reference value for subway safety evaluation of similar projects.

2. Selection of Constitutive Model

The key of numerical simulation analysis is the selection of constitutive model [15], and when conducting the numerical calculation of geotechnical engineering, it is necessary to take the soil constitutive model into consideration. At present, there are only a few constitutive models used in the software of finite element analysis, which are mainly divided into nonlinear and elastic-plastic models. [16] There are more than a dozen constitutive models available in Midas software, among which the failure criterion of Mohr-coulomb model is more accurate and the numerical analysis is more mature, which not only satisfies Hooke's law, but also follows Coulomb's failure criterion [17].

In this engineer, regarding the simulation of continuous medium, adopting hardening model constitutive relation in the calculation process, that is, Hardening-Soil model. HS model is an isotropic hardening elastic-plastic model, which can be applied to both soft soil and hard soil. The basic idea of HS model is similar to Duncan-Chang model. [18,19] Assuming that the relation between shear stress and axial stress in triaxial drainage test becomes hyperbola, but the former uses elastic-plastic to express this relation, instead of using elastic relation with variable modulus as Duncan-Chang model.

In addition, the shear dilation and neutral loading of soil are considered in the model, thus overcoming the shortcomings of Duncan-Chang model. Different from the ideal elastic-plastic model, the yield surface of HS model in principal stress space is not fixed, but can expand with plastic strain. The model can consider both shear hardening and compression hardening, and adopts Mohr-Coulomb failure criterion [20]. HS model has good accuracy when applied to excavation analysis of foundation pit.

In this engineer, the calculation element of soil material is the 15 nodes triangles; Linear elastic model is used to simulate concrete structural members, and the interaction between soil and underground structure adopt Goodman contact element. For the simulation of excavation process of foundation pit, by using the "element birth and death" of finite element software to simulate the construction process of underground diaphragm wall, layered excavation of each layer of soil and construction process of each support in the foundation pit engineering, and the whole process of excavation of foundation pit is simulated according to the whole process of "smooth practice" construction condition in the foundation pit engineering. The computation model includes soil, envelop enclosure, supporting system, adjacent buildings, subway structure and its foundation and other structural members.

3. Engineering Overview

A 147m super high-rise tower with 34 floors above ground is planned to be built in this project site, and its main function is hotel and office. The project generally constructs 4 basements, and the elevation of the bottom plate of the main basement structure is -19.250 m. The project consists of 2 foundation pits: The main foundation pit of the basement, and the foundation pit of the external lane on the south side. The total foundation pit area of the main basement is about 18000 m^2, and the total extension meter around foundation pit is about 627 m; The total foundation pit area of the external lane is about 980 m^2, and the total length around foundation pit is about 235 m.

The surrounding environment of foundation pit is complex. The north side of foundation pit is adjacent to Metro Line 1 station, and the subway running tunnels and river courses are temporarily relocated to drainage culvert pipes; The northwest side is adjacent to the No. 3 entrance and exit of subway station, the east side is adjacent to the municipal main roads, and the south side is adjacent to the residence. The foundation pit is about 28 m away from the subway, which has entered the range of twice the excavation depth of the foundation pit.

Considering the influence on adjacent subway structures to a certain extent caused by the following factors, such as the project is adjacent to subway stations, subway running tunnels, subway entrances and exits, the excavation and unloading of the foundation pit, which is mainly reflected in the displacement increment of subway structures and the deformation curvature of running tunnel caused by excavation of the foundation pit.

To sum up, adopting Midas GTS calculation software, combined with the characteristics of the engineering, aiming at the above adverse effects, analyzing the influence of excavation of the foundation pit on the adjacent subway section structure, and evaluating the subway safety. In order to ensure the safety of the normal operation of the subway, necessary measures are adopted for the construction of deep foundation pits.

4. Geological Conditions of the Site

Clay and silty clay are dominant in the excavation depth of foundation pit, and the basement is generally located in the clay and partially located in silty clay layer. The shallow soil layer of the site changes drastically, and silty clay with silty soil and silty clay fluctuates greatly, showing the distribution state of missing parts, and in some locations with extremely thick parts, the soil properties of the above soil layers have the characteristics of high compressibility, low strength, low permeability and high sensitivity, which are easy to generate rheological phenomena when excavating the foundation pit, resulting in increased internal force of envelop enclosure, poor stability and difficulty in controlling deformation. The shallow part of the site is filled with thick soil with poor soil properties, and the explored underground obstacles and unfavorable geology include: Backfilled blind ditch, existing river courses to be backfilled later, shallow miscellaneous garbage, locally distributed mud, old revetment foundation, landfill bridge (box culvert), slope protection surface layer, as well as rebar and soil nail set up for excavation of foundation pit of the second-stage residential building on the south side, etc. Before the construction of foundation pit, it is necessary to find out the distribution situation, and do a good job of clearing obstacles within the surrounding envelope structure.

The soil layer in the deep part of the site is evenly distributed, but the silty clay (mainly soft plastic) suddenly thickens on the northeast side of the site, and the clay with silty clay (plastic) becomes thinner or even missing. In terms of depth, the change appears at the embedded position at the bottom of the enclosure wall. Pay attention to the checking calculation and recheck of the pit bottom anti-uplift of the envelope enclosure in this range, to ensure the stability of the excavation stage of the foundation pit.

Silt micro-confining aquifers are generally distributed in the shallow layer of the foundation pit, and silt confining aquifers are locally distributed in the deep layer-the former is within the excavation depth of the foundation pit- the former is within the excavation depth range of the foundation pit. At this time, it is necessary to prepare for impermeability and leakage prevention of curtain to avoid soil erosion caused by local leakage, resulting in excessive settlement of surface, pipelines and buildings; The latter will make the stability of foundation pit against confined water surge insufficient when it is excavated to the base. At this time, it is necessary to conduct curtain isolation or reduce pressure and precipitation, so as to avoid water and sand surging and cause instability of the foundation pit.

5. Subway Safety Assessment and Monitoring Requirements

This engineering has large area of the foundation pit, deep excavation depth, large earthwork quantity and long construction period. In order to ensure the safety of construction and the smooth progress of excavation, it is necessary to carry out the whole process monitoring, dynamic management and information construction in the whole construction process. According to many engineering experiences of deep excavation of the foundation pit, on-site monitoring is an essential and important link for earthwork excavation and basement construction of deep excavation of the foundation pit. Only through on-site monitoring can we obtain the stress and deformation situation of envelope enclosure and surrounding soil in the process of foundation pit excavation in time, master the influence of foundation pit excavation on surrounding environment, effectively guide the construction, adjust construction measures in time, and ensure the normal operation of subway structure.

During the construction, the whole process monitoring of the sinking and bumping of lattice column, envelop enclosure displacement, tunnel displacement and ground surface settlement should be carried out to ensure the safety of the tunnel. This foundation pit engineering is adjacent to the completed subway station and running tunnel, which requires high deformation of tunnel structure. It is necessary to formulate a special subway safety protection monitoring scheme for subway running tunnel, implement information construction in the whole process, carry out real-time feedback analysis on monitoring results, improve the emergency plan for subway structure deformation, and take measures such as adjusting excavation scheme and increasing stages when necessary, to ensure construction safety.

During the construction of deep foundation pit excavation, the monitoring shall be conducted on the main structure of subway, section tunnel, No. 2 and No. 3 entrances and exits; The monitoring period is from the beginning of pile foundation construction to the completion of structure construction, and the deformation of subway structure tends to be stable; Monitoring frequency is determined by building risk level and adjusted according to stability situation of the data. The main monitoring items, monitoring standards and monitoring alarm values of subway structure during the project construction are shown in Table 1 below.

Table 1. Monitoring Items and Control Indexes of Subway Safety Protection

Control index			Monitoring index in safety protection zone of operation line (mm)		
			Early warning value	Alarm value	Control value
Running tunnel	Structure	Horizontal displacement of structure	5	8	10
		Vertical displacement of structure	5	8	10
		Tunnel radial convergence	5	8	10
	Track	Transverse height difference of track	1.5	2.4	3
		Orbital height difference (vector value)	1.5	2.4	3
		Track spacing	-1.5+2.4	- 2.4+ 3.8	- 3+ 4.8
Entrance and exit	Structure	Horizontal displacement of structure	5	8	10
		Vertical displacement of structure	5	8	10
		Opening amount of deformation joint	0.75	1.2	1.5
	Equipment	Vertical differential deformation of escalator	2	3	4
		Horizontal differential deformation of escalator	2	3	4
Main body of station	Structure	Horizontal displacement of structure	5	8	10
		Vertical displacement of structure	5	8	10

The foundation pit of this engineering belongs to deep and large foundation pit. During the construction period, the monitoring of foundation pit engineering should be strengthened. The main monitoring items should be monitored according to the requirements of Class I foundation pit in the Specification [21]. The monitoring items and alarm values of foundation pit engineering are shown in Table 2.

Table 2. Monitoring Items and Control Indexes of Foundation Pit Engineering

Monitoring content	Deformation rate alarm (mm/d)	Cumulative control value (mm)
Horizontal displacement of envelope enclosure	≥3	0.15%H and not exceeding 20
Vertical displacement of envelope enclosure	≥4	0.15%H and not exceeding 20
Water level outside the pit	500mm	1000mm
Land settlement	≥3	20mm

6. Numerical Analysis of Subway Safety Assessment

6.1 Establishment of Three-dimensional Numerical Model

In order to truly simulate the influence of foundation pit on adjacent subway running tunnels, it is necessary to establish a three-dimensional numerical model according to the actual terrain of the site and the distribution of foundation pit and subway tunnels, and divide the finite element mesh. The simplified computation model is shown in Figure 1.

The size of the computation model is determined according to the project site and surrounding environmental conditions, and considering the elimination of boundary effect. The size of the computation model is 278m wide in X direction, 415m in Y direction and 100m in Z direction.

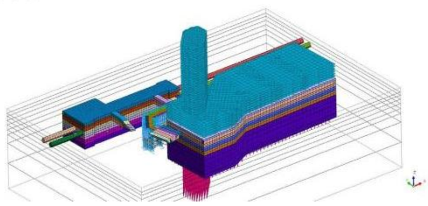

Figure 1. Mesh Model 2

In order to simplify the calculation, the following assumptions are assumed in the simulation:

1) The same layer of soil is homogeneous, isotropic and ideal elastic plastic body, and adopting the modified Mohr-Coulomb yield criterion;

2) The tunnel segment ring is assumed to be a continuous homogeneous elastic ring with equivalent stiffness;

3) It is not considered that the detachment phenomenon among tunnel lining, diaphragm wall and retaining pile and the soil, it is believed that they are always coordinated deformation;

4) The foundation pit adopts closed diaphragm wall for waterproofing, and the connecting passage adopts soil mixing wall. The construction depth of the river course is relatively shallow, which only involves surface

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diving, besides, a triaxial mixing pile is used to isolate the adjacent subway side, so the influence of drainage and precipitation seepage during construction is not considered for the time being in this calculation.

6.2 Establishment of Numerical Models under Different Working Conditions

According to the actual construction process, from data collection and analysis, model planning and establishment (3D model), initial gravity field calculation, gravity field initialization crustal stress balance, subway structure, equilibrium analysis of site after heaped load, river course pile foundation construction near subway side, construction of foundation pit diaphragm wall, excavation - support to base, backfilling and compaction - dismantling and supporting to plus or minus zero, construction soil mixing wall - channel excavation, channel structure backfilling and compaction - river course excavation, tower structure backfilling and compaction construction, computation system internal force and change - results analysis and summary of the main working conditions of the step calculation analysis, establishing three-dimensional numerical models of excavation, subway tunnel and surrounding stratum distribution based on Midas-GTS program. The three-dimensional models under different working conditions are shown in Figure 2-7.

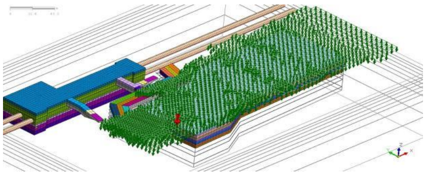

Figure 2. Working Condition 1- Initial Working Condition (Stacking Soil)

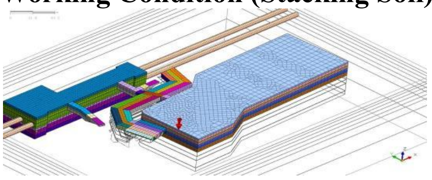

Figure 3. Working Condition 2- Soil Cleaning

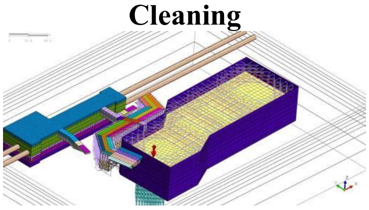

Figure 4. Working Condition 3- Foundation Pit Excavation to Base

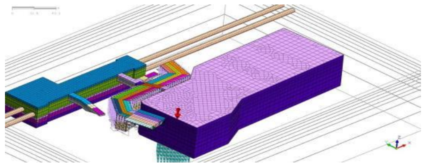

Figure 5. Working Condition 4- Foundation Pit Backfilling and Compaction to Plus or Minus Zero

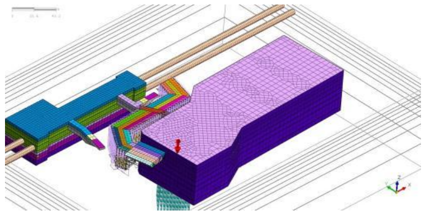

Figure 6. Working Condition 5-Excavation of Connecting Passage

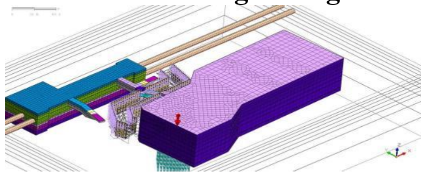

Figure 7. Working Condition 6- Excavation of Relocated River Course

6.3 Numerical Simulation Results

Conducting numerical simulation to three-dimensional model of deep foundation pit excavation under different working conditions, and the calculation results of horizontal and vertical displacements of subway structure are shown in Figure 8-Figure 16.

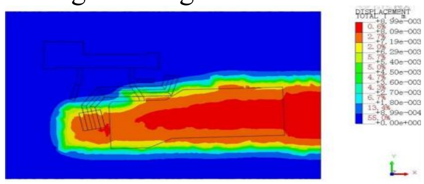

Figure 8. Cloud Chart of Stratum Deformation after Soil Cleaning

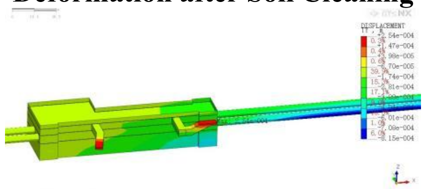

Figure 9. Horizontal Deformation Cloud Chart of Subway after Soil Cleaning

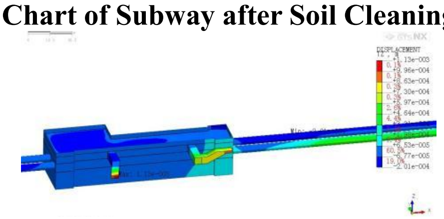

Figure 10. Cloud Chart of Vertical Deformation of Subway Structure after Soil Cleaning

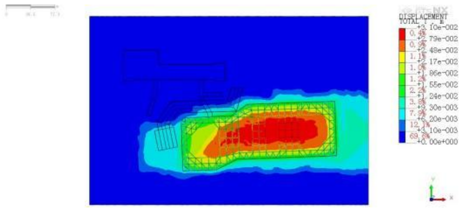

Figure 11. Cloud Chart of Stratum Deformation from Foundation Pit Excavation to Base

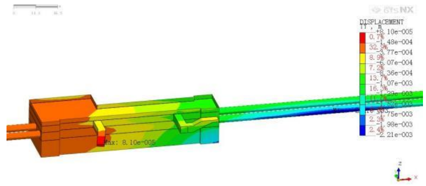

Figure 12. Horizontal Deformation Cloud Chart of Subway from the Excavation of Foundation Pit to Base

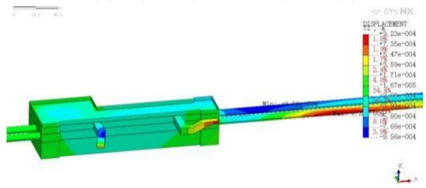

Figure 13. Cloud Chart of Vertical Deformation of Subway from the Excavation of Foundation Pit to Base

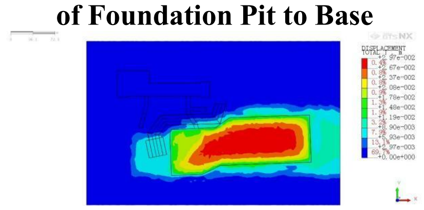

Figure 14. Cloud Chart of Stratum Deformation after Foundation Pit Backfilling and Compaction to Plus or Minus Zero

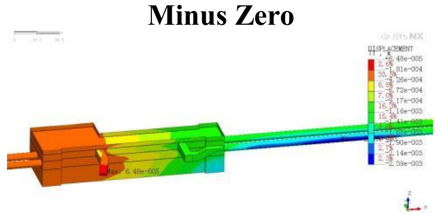

Figure 15. Horizontal Deformation Cloud Chart of Subway after Foundation Pit Backfilling and Compaction to Plus or Minus Zero

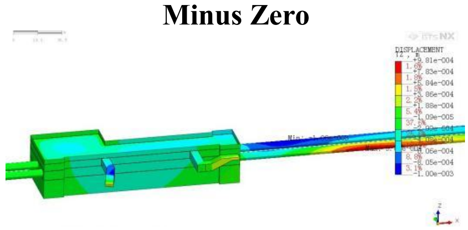

Figure 16. Cloud Chart of Vertical Deformation of Subway after Foundation Pit Backfilling and Compaction to Plus or Minus Zero

7. Analysis of Numerical Simulation Results

The following conclusions can be drawn from the calculation results:

(1) From the calculated deformation cloud chart, it can be seen that under the working condition of soil cleaning, due to the unloading effect of the ground, the deformation of the main structure of subway station and subway running tunnel is settlement. The entrance/exit of No. 2 and No. 3 are near the end, showing slight uplift, with the maximum horizontal displacement uplift value of 0.254 mm and the maximum vertical displacement uplift value of 1.13 mm.

(2) Under the working condition of excavation of the foundation pit to the base: For horizontal displacement, the end of entrance/exit of No. 3 near the foundation pit shows slight uplift, with the maximum uplift value of 0.08 mm, and the other parts show settlement, and the maximum value is that the running tunnel is adjacent to foundation pit side, with the maximum value of 2.21 mm; For vertical displacement, the foundation pit side of the running tunnel is uplift, with the maximum value of 0.923 mm, and the other parts are settlement, with the maximum value of 0.926 mm.

(3) Under the working condition of foundation pit backfilling and compaction to plus or minus zero: For horizontal displacement, the end of entrance/exit of No. 3 near the foundation pit shows slight uplift, with the maximum uplift value of 0.0648 mm, while the other parts show settlement, with the maximum value of 2.39 mm; For vertical displacement, the foundation pit side of the running tunnel is uplift, with a maximum value of 0.981 mm, and the other parts are settlement, with a maximum value of 1.000 mm.

(4) During the excavation of the foundation pit, the maximum horizontal displacement of the diaphragm wall adjacent to the subway is 20.2 mm. During the excavation and structural backfilling and compaction of the foundation pit, the maximum vertical displacement of the main body and its accessories of Park Station is -0.98 mm and the maximum horizontal displacement is -1.91 mm. The running tunnels are connected with each other by segments through bolts, and their own stiffness is relatively small. The maximum vertical displacement caused by the excavation and rebuilding of foundation pit is -1.00 mm and

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the maximum horizontal displacement is -2.39 mm, which meets the requirements of 10 mm deformation control standard of subway structured.

(5) Under each working condition, the maximum displacement is shown in Table 3 and Table 4. During the construction period, the maximum vertical displacement of subway running tunnel is -1.00 mm, and the maximum horizontal displacement is 2.83 mm, and the maximum horizontal convergence is 0.17 mm; During the construction period, the maximum vertical displacement of the main body of the station is 0.794 mm and the maximum horizontal displacement is 2.22 mm; During the construction period, the maximum vertical displacement of entrance/exit of No. 2 and No. 3 is 3.61 mm and the maximum horizontal displacement is 1.75 mm, which can meet the requirement of 10mm deformation control value of subway structure.

Table 3. Summary of Maximum Horizontal Deformation of Subway Structure under Different Working Conditions (mm)

Calculate working conditions		Running tunnel	Main body of station	Entrance/ exit of No. 2	Entrance/ exit of No. 3
1	Soil cleaning condition	-0.815	-0.577	-0.316	0.246
2	Excavation of the foundation pit to the base	-2.21	-1.85	-1.08	0.081
3	Foundation pit backfilling and compaction to plus or minus zero	-2.39	-1.91	-1.39	-0.453

Table 4. Summary Table of Maximum Vertical Deformation of Subway Structure under Various Working Conditions (mm)

Calculate working conditions		Running tunnel	Main body of station	Entrance/ exit of No. 2	Entrance/ exit of No. 3
1	Soil cleaning condition	0.541	0.195	0.915	1.130
2	Excavation of the foundation pit to the base	-0.956	-0.564	0.852	-0.914
3	Foundation pit backfilling and compaction to plus or minus zero	-1.000	-0.576	0.490	-0.908

(6) The minimum deformation curvature radius of running tunnel is 344204 m, which is larger than the minimum control radius of shield tunnel curvature of 15000 m. During the construction period, the maximum 10 m differential settlement difference of the running tunnel is 0.362 mm, which meets the requirements of track deformation.

To sum up, it can be considered that the excavation of the foundation pit will cause horizontal lateral displacement and vertical displacement of the adjacent subway tunnel structure to a certain extent, but the overall displacement is relatively small. Under normal construction conditions, the excavation of the foundation pit of this engineering will not endanger the safe operation of the adjacent subway.

8. Conclusions

With the help of Midas-GTS finite element numerical analysis software, establishing a three-dimensional model of "foundation pit-surrounding buildings- adjacent subway" for excavation of the foundation pit, and conducting the numerical simulation and analysis of the working conditions. Studying the influence of excavation of the foundation pit on the horizontal and vertical displacement of adjacent subway structures, and the following conclusions are drawn:

1) Comparing and analyzing the simulation data with the actual monitoring data, the results of the finite element software numerical simulation are consistent with the monitoring values of the construction site, which shows that the numerical model has certain rationality. The selection of parameters of Hardening-Soil model, Goodman contact element and other simulation models are correct, and the three-dimensional simulation is more in line with the actual situation of the engineering, which has certain guiding significance for similar engineerings in the later period.

2) The excavation of the foundation pit will cause horizontal lateral displacement and vertical displacement of adjacent subway structure to a certain extent, that is, the excavation deformation of the foundation pit has significant three-dimensional spatial effect. However, the maximum deformation of subway structure can be controlled within 10 mm, which belongs to the safety category compared with the monitoring items and control indexes of subway safety protection.

3) Under the condition that the construction organization and construction scheme are normal and reasonable, the deep excavation of the foundation pit will not cause obvious change in the stress state of the adjacent

subway running tunnel, and will not endanger the structural safety of the subway running tunnel and subway station.

Therefore, according to the numerical simulation results to guide the law, find the law, summarize the law, providing reference and basis for subway safety assessment, which has certain guiding significance for practical engineering.

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