

Numerical Simulation Study on the Impact of Foundation Pit Unloading on Adjacent Existing Subway Tunnels

Jian Xiong^a, Yahui Wang^b, Minjian Chen^c

Shenzhen Integrated Geotechnical Investigation & Surveying Co., Ltd., Shenzhen 518108, China

^a619735130@qq.com, ^b1072060863@qq.com, ^c1067589072@qq.com

Abstract

To further explore the impact of new foundation pit unloading on adjacent subway tunnels in various regions, a study was conducted based on a foundation pit project in Shenzhen. A three-dimensional numerical model was created using MIDAS GTS NX finite element software to simulate the new foundation pit project and the adjacent subway tunnel. The deformation of the foundation pit support structure, the settlement of surrounding soil, and the deformation of the existing subway tunnel under different excavation conditions were analyzed and compared with actual monitoring data. The results show that during foundation pit construction, both the support structure's deformation and the surrounding soil's settlement were relatively minor. The pile-anchor support scheme effectively controlled the foundation pit's deformation. The maximum horizontal and vertical displacements of the adjacent subway tunnel, induced by foundation pit excavation, occurred near the pit's center and gradually decreased towards both sides. As the foundation pit's depth increased, the maximum horizontal and vertical displacements of the tunnel structure also increased. After the foundation pit was backfilled, the deformation gradually decreased but did not reduce to zero. The tunnel structure's maximum horizontal and vertical displacements were 2.03mm and 0.95mm, respectively. The impact of foundation pit excavation on the tunnel structure's horizontal displacement was more significant than on its vertical displacement, but foundation pit dewatering had a greater impact on the vertical displacement. Comparing the numerical simulation results with actual measurements, the overall deformation pattern of the subway tunnel was consistent with the simulation, and the actual displacement was smaller than the simulated results. The foundation pit unloading had minimal impact on the adjacent subway tunnel, ensuring its normal operation.

Keywords

Foundation Pit Unloading; Adjacent Side; Existing Subway Tunnel; Numerical Simulation.

1. Introduction

To accommodate rapid urban development and meet transportation demands, many cities have recently planned and built large-scale subway systems. In cities with increasingly complete subway systems, new foundation pit projects (e.g., basements for high-rise buildings, underground commercial centers) inevitably border existing subway lines. Excavating foundation pits requires removing large amounts of soil, disrupting the soil's mechanical equilibrium and potentially affecting nearby subway tunnels. Ensuring the operational safety of subway systems, a vital component of urban transportation, is crucial for protecting lives and property. National regulations currently impose strict standards on subway tunnel deformation. However, in practical engineering, foundation

pit construction has often caused excessive displacement, deformation, or even accidents in adjacent subway tunnels [1-3]. Therefore, studying the impact of new foundation pits on nearby subway tunnels is critically important.

In practical engineering, the relative position of new foundation pits to nearby subway tunnels usually falls into two categories: beside or beneath the foundation pit. The situation where the subway tunnel is beside the foundation pit is more common. The impact mechanisms of foundation pit excavation on adjacent subway tunnels are more complex than those of tunnels located beneath the pit [3].

Numerous domestic and international scholars have extensively researched the impact of foundation pit excavation on adjacent subway tunnels, achieving significant results. As early as the 1980s, Kusakabe et al. [4] conducted centrifugal model tests on the effects of foundation pit excavation on nearby pipelines. Zhang Zhiguo et al. [5] and Dai Hongwei et al. [6] conducted in-depth studies on subway tunnel deformation caused by foundation pit excavation using a two-stage analysis method. However, their analyses did not consider several practical factors, such as the three-dimensional temporal and spatial effects of excavation, the construction of retaining structures, and dewatering, leading to discrepancies with real-world engineering projects.

The finite element numerical analysis method, known for its efficiency, comprehensiveness, and realistic reflection of actual conditions, is widely applied in various engineering fields. In geotechnical engineering, the finite element method realistically reflects soil and rock constitutive relationships during analysis, considering multiple factors and complex boundary conditions, thereby revealing the essence of soil and rock instability [7]. Based on field monitoring data and past engineering experience, Yang Jun et al. [8] used FLAC 3D finite element difference software to analyze the impact of foundation pit excavation on nearby subway tunnels and proposed a gravitational field concept for the aggregation of soil displacement outside the excavation pit. ZHENG et al. [9] developed a finite element analysis model using a small strain stiffness hardening soil model, investigating the effects of excavation depth, horizontal displacement of supporting structures, and other factors on nearby tunnel deformation, and proposed a simplified model for predicting and evaluating tunnel deformation.

Although the numerical research methods mentioned above generally provide similar insights into the impact of foundation pit excavation on nearby subway tunnels, regional differences and varying conditions necessitate further in-depth research into the impact patterns.

This paper, based on a newly constructed foundation pit project beside a subway tunnel in Shenzhen, uses MIDAS GTS NX finite element software to establish a three-dimensional numerical model of the new foundation pit and the adjacent subway tunnel. It analyzes the internal forces and deformations of the foundation pit's retaining structure and the subway tunnel under different excavation conditions. By comparing the results with actual monitoring data, the paper derives the impact patterns of foundation pit excavation on adjacent subway tunnels, aiming to provide practical guidance for engineering projects.

2. Project Overview

2.1 The Relationship between the New Foundation Pit and the Relative Position of the Existing Subway Tunnel

This paper focuses on a foundation pit project in Shenzhen, where the new pit is adjacent to an existing operational subway tunnel. The layout of the new foundation pit in relation to the subway tunnel is shown in Figure 1.

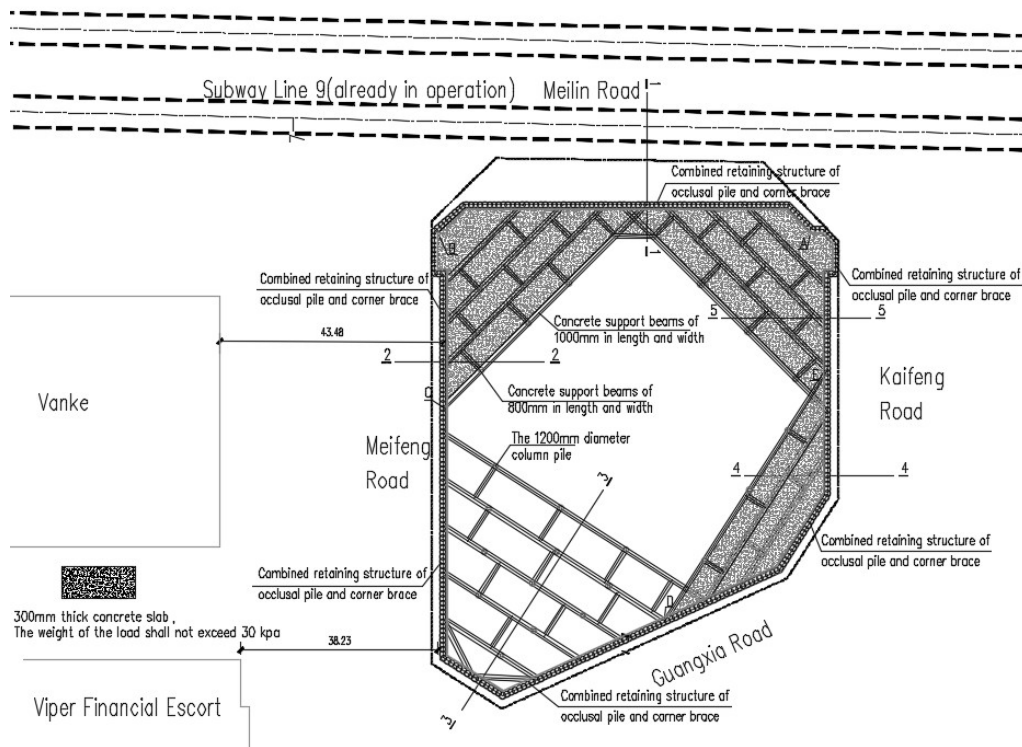


Figure 1. Layout plan showing the relationship between the new foundation pit and the subway tunnel

The foundation pit has a polygonal shape, surrounded mainly by industrial and residential areas, with the north side adjacent to an operational subway. The excavation area of the pit is 6039.14m², with a maximum width of 94m and a depth ranging from 17.8 to 19.6 meters. The northern side of the pit runs nearly parallel to the subway line, with the nearest distance from the project boundary to the subway structure being about 3.4 meters, and the distance from the excavation edge to the subway about 12 meters. The subway tunnel has a burial depth of 14.4 meters, a diameter of 6.0 meters, and a segment thickness of 300mm.

2.2 Site Engineering Geological Conditions

According to the geological survey report, the soil layers are, from top to bottom: Quaternary artificial fill and miscellaneous fill (Q^{ml}); Holocene alluvial and proluvial silty clay, clay, and gravelly sand (Q^{al+pl}); Quaternary residual gravelly clay (Q^{el}); with underlying bedrock consisting of Jixian and Qingbaikou Systems' Yinuhugroup mixed granite (Jx-Qby).

2.3 Foundation Pit Retaining Structure Types

Choosing the type of retaining structure is crucial for ensuring the safety of foundation pit construction. Considering the surrounding environment, geological conditions, and deformation requirements, the support scheme for the pit combines interlocked piles and diagonal bracing with three internal supports. To further ensure the subway tunnel's safety, the reinforced interlocked piles on the side adjacent to the tunnel have a diameter of 1.2 m and a spacing of 1.8 m; unreinforced piles have the same diameter and spacing. Both pile types are embedded 8.0 m into the pit bottom, with a 300mm thick concrete slab installed at the first support level. On the remaining sides, the reinforced piles have a diameter of 1.2 m, and the unreinforced piles have a diameter of 1.0 m, both with a spacing of 1.8 m; the reinforced piles are embedded 7.0 m into the pit bottom, while the unreinforced piles are embedded 4.0 m deep. A 300mm thick concrete slab is also installed at the first support level on the pit's east side. The retaining structure on the pit's north side and the cross-sectional diagram of the subway tunnel are shown in Figure 2.

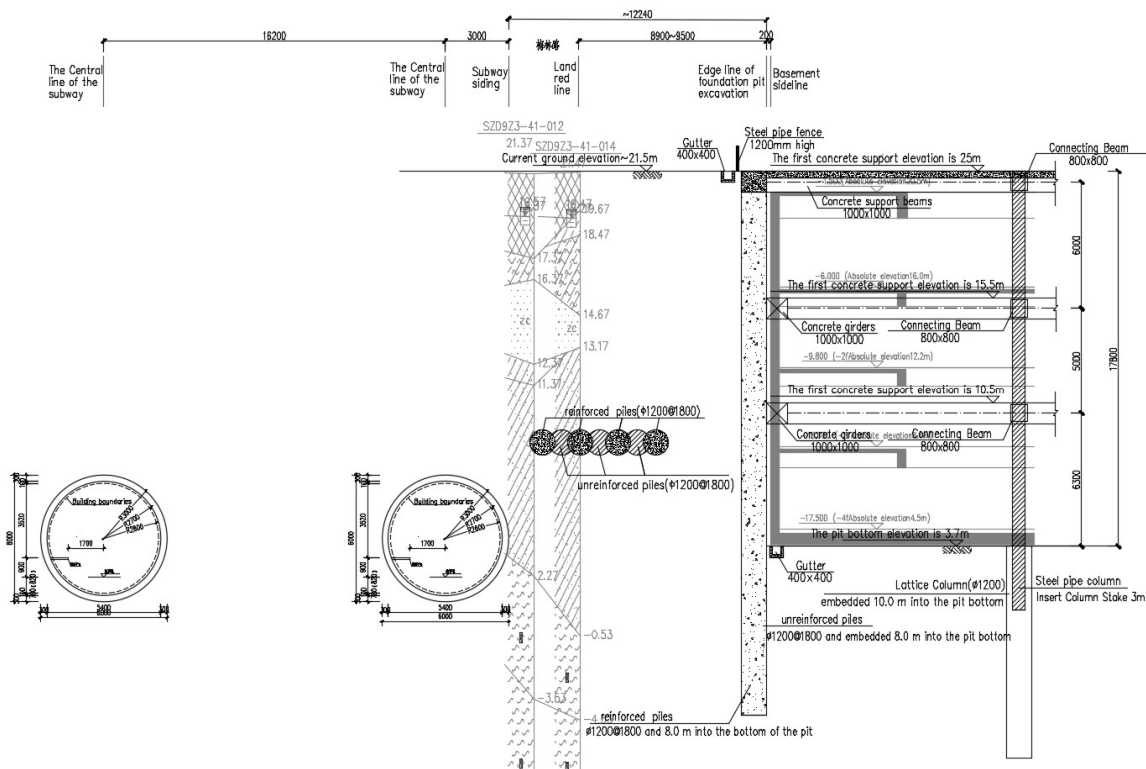


Figure 2. Cross-Section Diagram of the Foundation Pit Retaining Structure and the Subway Tunnel

3. Numerical Simulation

3.1 Model Establishment

Based on the excavation boundary, tunnel geological profile, and position relationship between the foundation pit and subway tunnel, a 3D numerical model was established using MIDAS GTS NX finite element software. To eliminate boundary effects and account for the number of elements and calculation accuracy, the model extends the excavation boundary by three times the pit depth. The model dimensions are 210 m (X) × 190 m (Y) × 75 m (Z), with the groundwater level set at -3.0 m.

In the model, soil layers use the Hardening-Soil model, each assumed to be an ideal elastoplastic body, while the subway tunnel and foundation pit retaining structures are assumed to be linear elastic bodies. 3D solid elements analyze stress and deformation in the soil layers, 2D plate elements simulate the retaining structures, and 1D beam elements simulate the support beams, columns, and uplift piles within the foundation pit. The cutoff wall is simulated using interface elements with a permeability coefficient of 0.

The model boundaries are displacement boundary conditions, with the top surface as a free boundary, the bottom surface fixed, the left and right boundaries fixed in the X direction, and the front and rear boundaries fixed in the Y direction. The 3D numerical model contains approximately 120,000 finite elements. The 3D numerical model of the foundation pit-soil-subway tunnel is shown in Figure 3.

The subway tunnel lining, foundation pit retaining structure, and cover slab use shell elements, while the crown beam, waist beam, column piles, and support beams use 1D elements. The numerical model of the foundation pit and subway structure is shown in Figure 4.

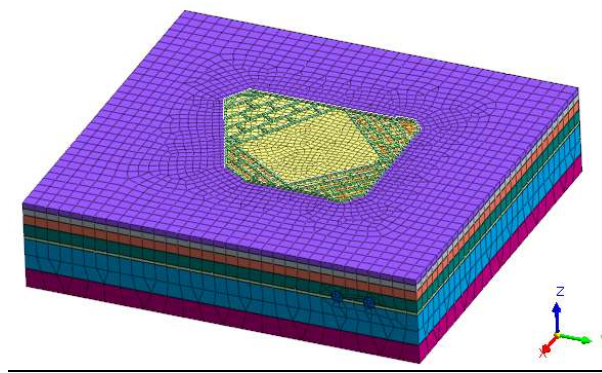


Figure 3. 3D Geometric Model of the Foundation Pit-Soil-Subway Tunnel

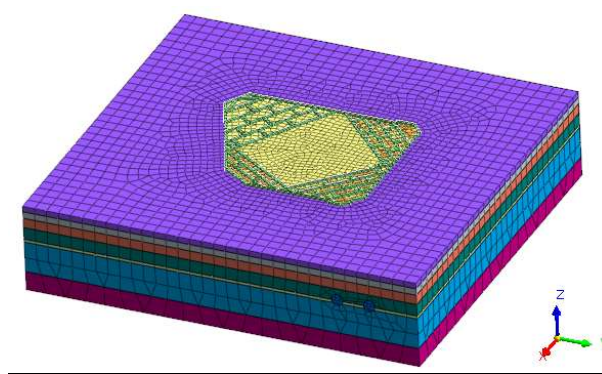


Figure 4. Geometric Model of the Foundation Pit and Subway Tunnel Structure

3.2 Parameter Selection

The geotechnical and tunnel structure parameters required for model analysis are primarily derived from the site survey report, subway tunnel data, and relevant regional standards. The geotechnical parameters, section dimensions, and physical-mechanical properties of the foundation pit and subway tunnel support structures are shown in Tables 1 and 2.

Table 1. Geotechnical Physical and Mechanical Parameters

Stratum Name	Constitutive Model	γ ($\text{kN}\cdot\text{m}^{-3}$)	ν	c	Φ (kPa)	E_0 (MPa)
Miscellaneous Fill	Ideal Elastoplastic	1.80	0.35	10	8	4
Silty Clay	Ideal Elastoplastic	1.70	0.4	8	3	3
Clay	Ideal Elastoplastic	1.85	0.32	20	16	8
Gravelly Sand	Ideal Elastoplastic	2.00	0.25	0	30	20
Gravelly Clay	Ideal Elastoplastic	1.90	0.3	20	20	15
Completely Weathered Granite	Ideal Elastoplastic	1.95	0.28	28	25	50
Highly Weathered Granite	Ideal Elastoplastic	1.98	0.24	33	30	80
Moderately Weathered Granite	Ideal Elastoplastic	2.20	0.22	150	45	250
Reinforced Concrete	Linear Elastic	2.50	0.20	---	---	---

Table 2. Section Dimensions and Physical-Mechanical Properties of Support Structures

Interlocked Pile (Equivalent to Continuous Wall)	C30 Reinforced Concrete	Wall Thickness 850	31500	0.2
Crown Beam	C30 Reinforced Concrete	1200×1000	31500	0.2
Support Beam	C30 Reinforced Concrete	1000×1000	31500	0.2
Connecting Beam	C30 Reinforced Concrete	1200×800	31500	0.2
Column Pile	C30 Reinforced Concrete	∅1200	31500	0.2
Lattice Column	Steel Pipe	∅609	206000	0.2
Shield Tunnel Segment	C50 Reinforced Concrete	Thickness 300	34500	0.2

3.3 Simulated Excavation Conditions

In this numerical simulation, the consolidation of drained soil is considered, but the effects of retaining structure construction on soil disturbance and the impact of partitioned excavation and surrounding load are not. In MIDAS GTS NX, the excavation and support of the foundation pit are simulated using load steps, deactivation, and activation of elements.

This paper conducts a step-by-step simulation based on the actual construction process, with appropriate simplifications, considering the temporal and spatial effects of the foundation pit excavation. As the subway tunnel already exists during the new foundation pit excavation, detailed simulation of the tunnel construction is not performed, and the soil disturbance caused by tunnel construction is not considered. After simulating tunnel excavation, station elements are activated, and displacements are reset to zero. The workflow for analyzing each construction stage is shown in Table 3:

Table 3. Geotechnical Physical and Mechanical Parameters

Construction Phase	Sequence Number	Condition	Simulation Content
Pre-Excavation Phase	1	Model Establishment	Initialize balance calculation before excavation to form the initial stress field.
	2	Displacement Reset	Reset the displacement caused by gravity in step 1, retaining only the initial stress.
	3	Tunnel Excavation	Simulate the excavation to form the subway Line 9 tunnel structure.
	4	Second Displacement Reset	Reset the displacement caused by tunnel excavation, retaining only the initial stress.
Excavation Phase	5	Condition 1	Construct secant piles, columns, and engineering piles at ground level (elevation ±0.0m).
	6	Condition 2	First excavation down to -1.5m, then construct the first support, crown beams, and concrete capping beams on pile tops.
	7	Condition 3	First dewatering of the foundation pit down to -18.5m (initial water level at -3.0m).
	8	Condition 4	Second excavation down to -7.0m, then construct the second support.
	9	Condition 5	Third excavation down to -12.0m, then construct the third support.
	10	Condition 6	Fourth excavation down to the pit bottom (depth -17.8m).
Backfilling Phase	11	Condition 7	Fifth excavation of the bottom pit and deeper foundation slab.
	12	Condition 8	Construct the basement slab, exterior walls, and the fourth basement floor slab, remove the third internal support, and backfill the pit.
	13	Condition 9	Construct the basement exterior walls and the third basement floor slab, remove the second internal support, and backfill the pit.
	14	Condition 10	After removing the first support and completing the entire basement structure, finish backfilling the pit.

4. Numerical Simulation Results Analysis

4.1 Lateral Deformation Analysis of Foundation Pit Retaining Structure

The foundation pit in this project employs a support scheme of interlocked piles and diagonal bracing. Figures 5-6 illustrate the cloud diagrams of lateral displacement changes in the foundation pit retaining structure during the excavation.

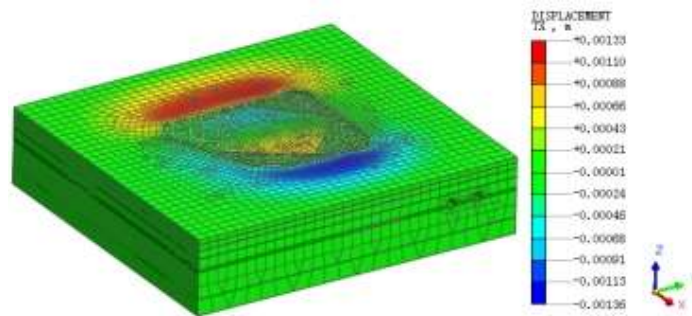


Figure 5. Horizontal Displacement Cloud Diagram at -1.5m Excavation Depth

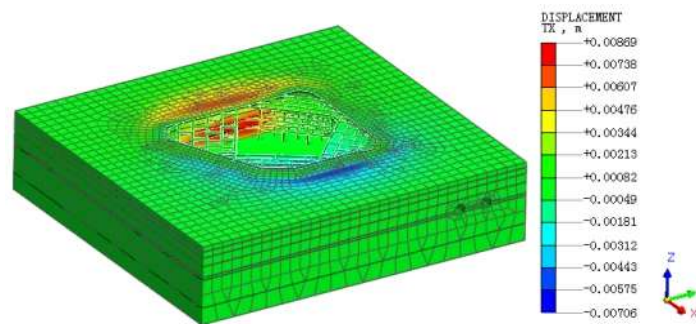


Figure 6. Horizontal Displacement Cloud Diagram at Full Excavation to Pit Bottom

Figures 5-6 reveal that during excavation, the horizontal displacement of the retaining structure is greatest in the middle and gradually decreases towards both ends. This occurs because the retaining structure has adjacent side piles for support at both ends, while central support is weaker. Additionally, the horizontal displacement of the retaining structure parallel to the subway side is smaller than that perpendicular to it. When excavation reaches the bottom, it indicates that the reinforcement near the subway effectively suppressed foundation pit deformation.

4.2 Vertical Deformation Analysis of the Surrounding Soil Layer

The foundation pit in this project employs a support system of interlocked piles and diagonal bracing. Figures 7-8 illustrate the cloud diagrams of vertical displacement changes in the surrounding soil layer during the excavation.

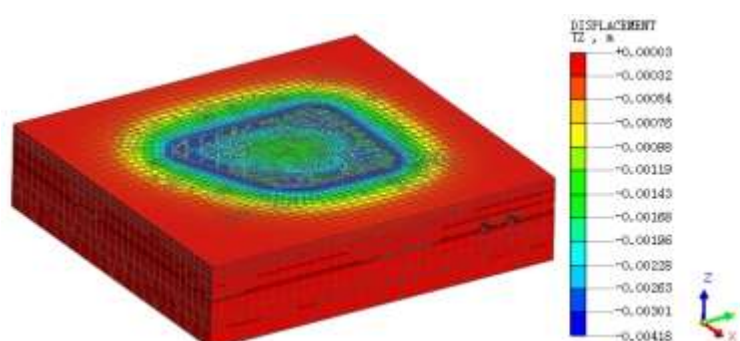


Figure 7. Vertical Displacement Cloud Diagram at -1.5m Excavation Depth

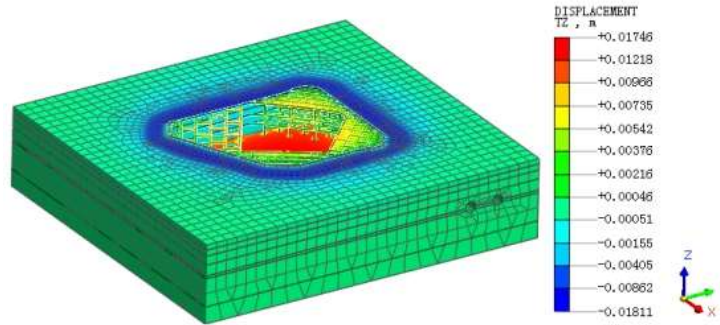


Figure 8. Vertical Displacement Cloud Diagram at Full Excavation to Pit Bottom

Figure 6 shows that the surrounding soil experiences settlement deformation after the excavation, with the greatest settlement near the pit and gradually decreasing with distance. This is due to the decreasing unloading effect of the foundation pit on the surrounding soil as the horizontal distance increases.

4.3 Internal Force Analysis of Foundation Pit Retaining Structure

Figure 9 presents the moment diagrams of the foundation pit's crown beams and support beams at full excavation to the bottom.

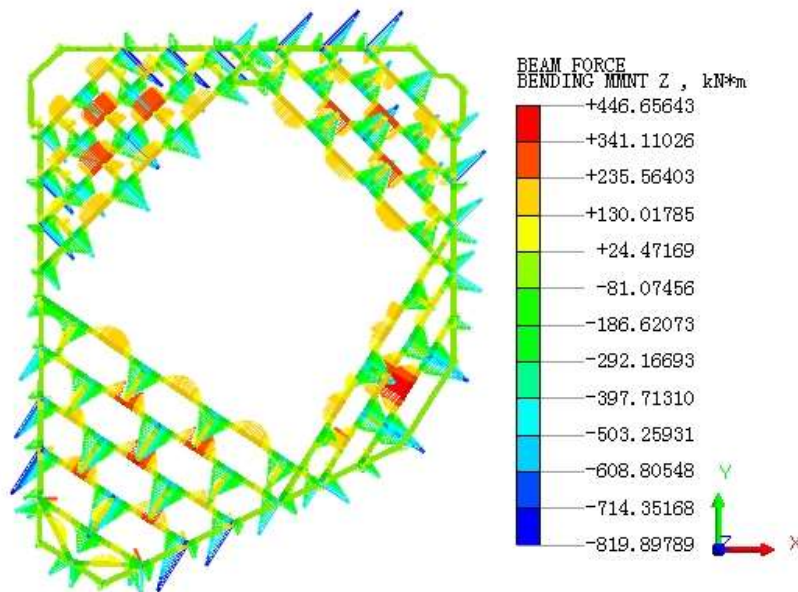


Figure 9. Moment Diagrams of Crown Beams, Support Beams, and Other Structures

Figure 9 presents the moment diagrams of the foundation pit's crown beams and support beams at full excavation to the bottom. This suggests that the internal support arrangement of the foundation pit is reasonable.

4.4 Deformation Analysis of Existing Subway Tunnel

Figures 10-11 illustrate the displacement cloud diagrams of the subway tunnel structure during excavation. Figure 12 displays the curves of maximum horizontal and vertical displacement of the tunnel structure under different conditions. In the figures, negative vertical displacement represents settlement, and negative horizontal displacement indicates movement toward the foundation pit.

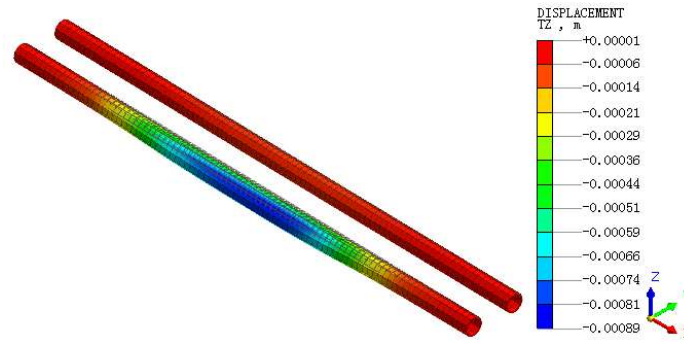


Figure 10. Vertical Displacement Cloud Diagram of Subway Tunnel at -1.5m Excavation Depth

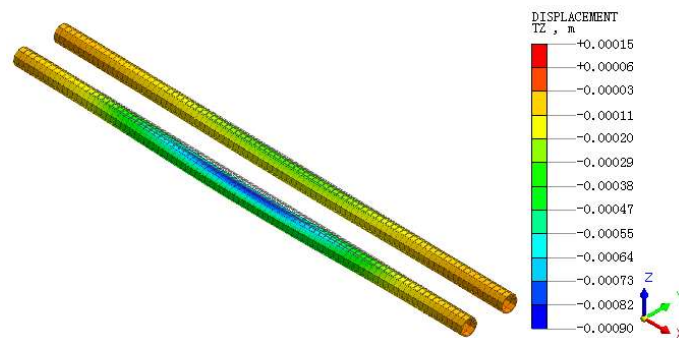


Figure 11. Vertical Displacement Cloud Diagram of Subway Tunnel at Full Excavation to Pit Bottom

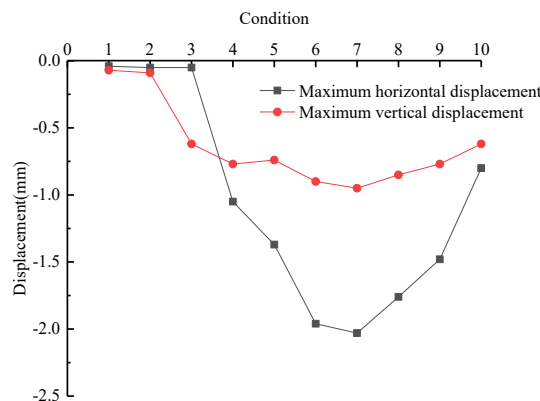


Figure 12. Maximum Displacement Variation of Tunnel Structure Under Different Conditions

Figures 10 and 11 show that the maximum horizontal and vertical displacements of the tunnel structure are near the middle of the adjacent excavation pit and gradually decrease toward both ends. Figure 12 clearly shows that as excavation depth increases, the maximum horizontal and vertical displacements of the tunnel structure also rise. After backfilling, the deformation gradually decreases but does not return to zero. This is because the deformation of the tunnel structure cannot fully recover in a short time. The maximum horizontal and vertical displacements of the tunnel structure occur in condition 7 (i.e., after excavation completion), with values of 2.03 mm and 0.95 mm, respectively, both meeting the deformation control requirements for subway tunnels, which mandate deformation below 10 mm.

The tunnel structure's vertical displacement is 0.09 mm in condition 2 (when excavated to -1.5 m) and suddenly rises to 0.62 mm in condition 3 (when the water table is lowered to -18.5 m). This is due to dewatering, which creates a funnel that causes surrounding soil to settle, leading to vertical

deformation of the tunnel structure. As the excavation depth continues to increase, the tunnel structure's vertical displacement stabilizes, with the maximum increase being around 0.15 mm.

The tunnel structure's horizontal displacement is -0.05 mm in condition 3 (after lowering the water table to -18.5 m) and suddenly increases to -1.05 mm in condition 4 (after excavation to -7.0 m). This occurs because unloading the soil inside the pit creates a dewatering funnel, causing settlement and horizontal deformation of the tunnel structure. As the excavation depth increases, the tunnel structure's horizontal displacement continues to rise.

Overall, excavation has a more significant impact on the tunnel structure's horizontal displacement than its vertical displacement, while dewatering has a greater effect on vertical displacement.

5. On-site Monitoring of the Existing Subway Tunnel

5.1 Monitoring Point Layout

To ensure the safety of the adjacent subway tunnel during excavation, deformation monitoring was conducted. Figures 13 and 14 show the layout of the excavation pit monitoring points and the subway tunnel observation sections.

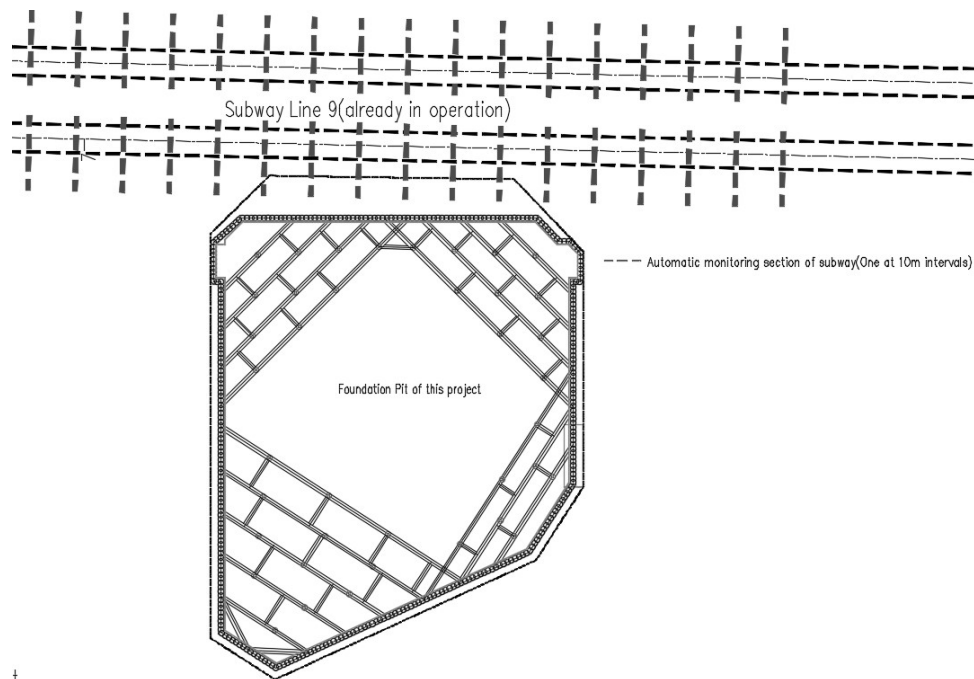


Figure 13. Layout of Monitoring Points for the Excavation Pit

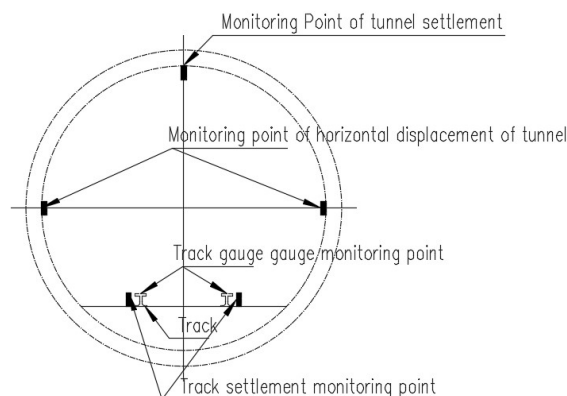


Figure 14. Cross-section diagram of the subway tunnel monitoring point

5.2 Comparison of Measured and Simulated Results

During excavation, the maximum horizontal and vertical displacements of the adjacent subway tunnel structure were measured and compared to the numerical simulation results, as shown in Figure 15.

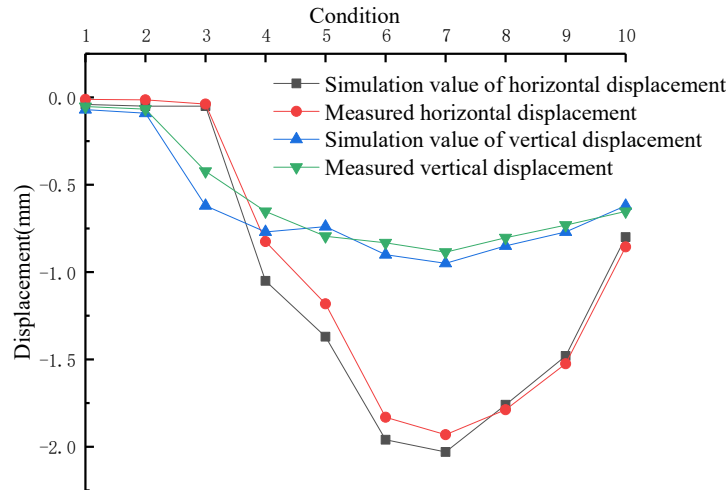


Figure 15. Comparison of Simulated and Measured Maximum Displacements of the Tunnel Structure Under Different Conditions

Figure 15 shows that the overall trend of the numerical simulation results for the deformation of the adjacent subway tunnel induced by excavation is consistent with the measured deformation. Additionally, the actual displacement of the subway tunnel is smaller than the numerical simulation results, with only slight deviations. The maximum measured horizontal and vertical displacements of the tunnel structure are 1.93 mm and 0.89mm, while the numerical simulation results are 2.03 mm and 0.95mm. This indicates that the excavation design for this project is safe and reliable, having minimal impact on the adjacent subway tunnel.

6. Conclusion

This paper uses MIDAS GTS NX finite element software to establish a three-dimensional numerical model of a new excavation project and the adjacent subway tunnel in Shenzhen. The deformation of the excavation support structure and subway tunnel under various conditions is analyzed and compared with actual monitoring data, revealing the excavation's impact on the adjacent tunnel. The main conclusions are as follows:

Numerical simulations show that the maximum lateral displacement of the foundation pit support structure occurs at the center and gradually decreases toward both ends. The horizontal displacement parallel to the subway side is smaller than that perpendicular to it, indicating that reinforcement near the subway side effectively limits pit deformation.

Numerical simulations show that soil settlement decreases with increasing distance from the pit, with the largest settlement occurring closest to it. At the bottom of the pit, the maximum vertical displacement is 18.11 mm, meeting regulatory requirements. The support scheme minimally impacts the surrounding environment.

Numerical simulation results indicate that when the foundation pit is excavated to the bottom, the maximum bending moment of the support beam is 819.90 kN·m, which is less than the critical force of the support beam. This suggests that the internal support layout scheme of the foundation pit is relatively reasonable.

Simulations show that the maximum horizontal and vertical displacements of the tunnel structure occur near the center of the foundation pit and gradually decrease toward the sides. As excavation

depth increases, the maximum horizontal and vertical displacements of the tunnel structure also increase. After backfilling, the deformation gradually decreases but does not return to zero. The maximum horizontal and vertical displacements of the tunnel structure are 2.03 mm and 0.95 mm, both meeting subway deformation requirements. The foundation pit construction has a greater impact on the tunnel structure's horizontal displacement than its vertical displacement.

Actual monitoring data show that the deformation pattern of the adjacent subway tunnel induced by foundation pit construction is consistent with the simulations, with actual displacement being smaller than simulated results. The unloading of the foundation pit has minimal impact on the adjacent subway tunnel, ensuring its normal operation.

Acknowledgments

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