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Original Paper

Analysis of the Influence of Deep Foundation Pit Excavation with Diaphragm Wall Support on Deformation of Adjacent Metro Tunnels

Huanrong Zhang, Zhaoqiang Wu & Shouling Luan

Qingdao City University, Qingdao, Shandong 266106, China

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Abstract

On the north side of a deep foundation pit in Nanjing, the diaphragm wall support is located at a minimum net distance of only 12 m from an operational metro tunnel. To control the deformation of the metro tunnel, triaxial cement-soil mixing piles were adopted for slot wall reinforcement on both sides of the diaphragm wall. Based on this project, the MAIDAS/GTS finite element software was used to conduct 3D numerical simulations of the longitudinal and transverse displacements of the adjacent metro tunnel caused by deep excavation under diaphragm wall support. The effectiveness of the cement-soil mixing pile reinforcement measures was analyzed and compared through simulation calculations, aiming to provide references for similar designs and constructions.

Keywords

Metro, Deep Foundation Pit, Diaphragm Wall, Adjacent Tunnel, Deformation Analysis

1. Introduction

With the intensive development and utilization of urban underground space, deep foundation pit construction near metro lines is inevitable. The presence of metro tunnels and other structures makes the surrounding environment of the pit complex and highly sensitive. A typical example is the deep foundation pit of Nanjing Zifeng Tower, which is adjacent to 3 main roads, dense pipelines, and as close as 5 meters to the main structure of Nanjing Metro Line 1. In the case of another deep foundation pit in Nanjing discussed here, the minimum net distance to the operational Metro Line 2 tunnel is only 12 meters, and the surrounding area includes important buildings such as a Christian church (a cultural heritage protection site). For diaphragm wall-supported deep foundation pit projects in such complex environments near metro tunnels, advanced methods like 3D numerical analysis are employed to study the deformation laws of adjacent metro tunnels caused by excavation and propose corresponding protective measures. This research holds significant theoretical and practical implications for controlling and protecting existing metro structures and other buildings during urban deep excavation.

Currently, conventional support structure designs primarily rely on the Plane Vertical Elastic Beam Method and 3D Elastic Foundation Plate Method recommended by standards. Both methods can simulate actual working conditions and calculate the internal forces and deformations of the retaining structure and support system, with the 3D method additionally accounting for the spatial effects of the retaining structure. However, neither method can incorporate critical surrounding structures into the computational model, limiting their ability to directly assess environmental impacts. Therefore, these approaches have inherent limitations in analyzing the environmental effects of deep excavation. Liu Guobin et al. combined the residual stress method for soft soil heave deformation with the concept of soft soil unloading modulus to establish a computational model for pit heave deformation, deriving a formula to predict the uplift deformation of existing tunnels beneath the pit. The Continuum Finite Element Method is commonly used to analyze environmental effects caused by excavation. This method treats the retaining structure, surrounding soil within a certain influence range, and key structures as an integrated system, using the release of in-situ stress on the excavation surface as the load and employing element "birth-death" techniques to simulate soil excavation and support construction.

This study employs the 3D Finite Element Method to simulate the excavation of the deep foundation pit. The analytical model includes the retaining structure, the operational metro tunnel, and the surrounding soil within the influence range. Based on the computational results, corresponding measures are implemented in the design to control metro tunnel deformation.

2. Project Overview

The project in Nanjing consists of a main tower, commercial podium, and basement. The main tower has 48 floors with a structural height of 220 meters, while the commercial podium is 10 stories high. The excavation area covers approximately 12,400 square meters, with a perimeter of about 490 meters. The relative elevation of the basement foundation slab is -20.90 meters, and the total excavation depth of the pit area is 22.1 meters. The surrounding environment is complex: South side: Catholic Church (a cultural heritage protection unit), East side: Shopping mall (a key building), North side: Diaphragm wall (only 12 meters away from the metro tunnel), the metro tunnel adopts a box structure with a width of approximately 6.28 meters and a burial depth of 8.9 to 9.8 meters (Figure 1).

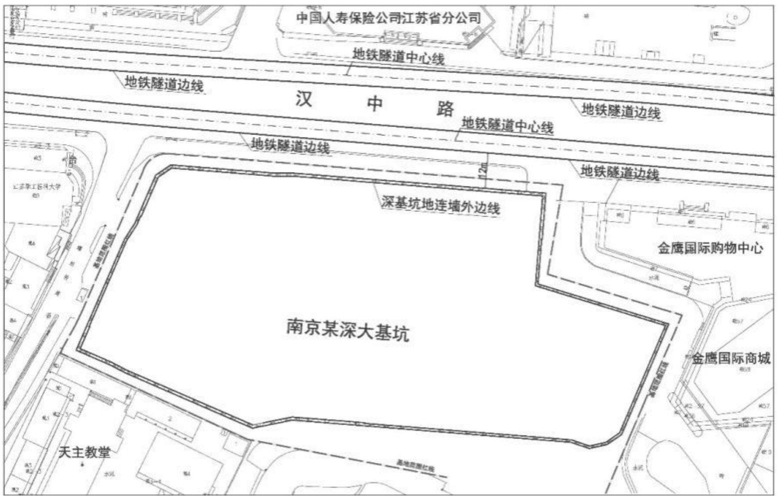

Figure 1. General Layout Plan of the Excavation Pit Construction Site

3. Support Structure Design

The perimeter of the excavation pit adopts a "two-in-one" diaphragm wall support structure, which serves as both the retaining structure for soil and water cutoff during deep excavation and the structural external wall of the basement. The diaphragm wall thickness is 800 mm in general areas around the pit and tower, while it increases to 1,000 mm on the north side near the metro area and the south side near the Catholic Church, with a depth of 34.1 meters. For the diaphragm wall adjacent to the metro side: Ground improvement: Triple-axis cement-soil mixing piles are used to reinforce the trench walls. Waterproofing: 850-mm-diameter high-pressure jet grouting piles are installed externally for sealing. Construction sequence: The triple-axis mixing piles are constructed first, followed by the diaphragm wall after achieving the required strength. Inside the pit, 4 reinforced concrete supports are installed: Vertical spacing: Based on engineering experience, the distances are set as: h_1 = 5.75 m, h_2 = 4.5 m, h_3 = 3.5 m, h_4 = 3.5 m, h_5 = 3.6 m, Depth: 20.9 meters, Horizontal spacing: 10 meters between supports, Cross-section dimensions: 800 mm × 800 mm for all supports, the support design profile near the metro tunnel is shown in Figure 2.

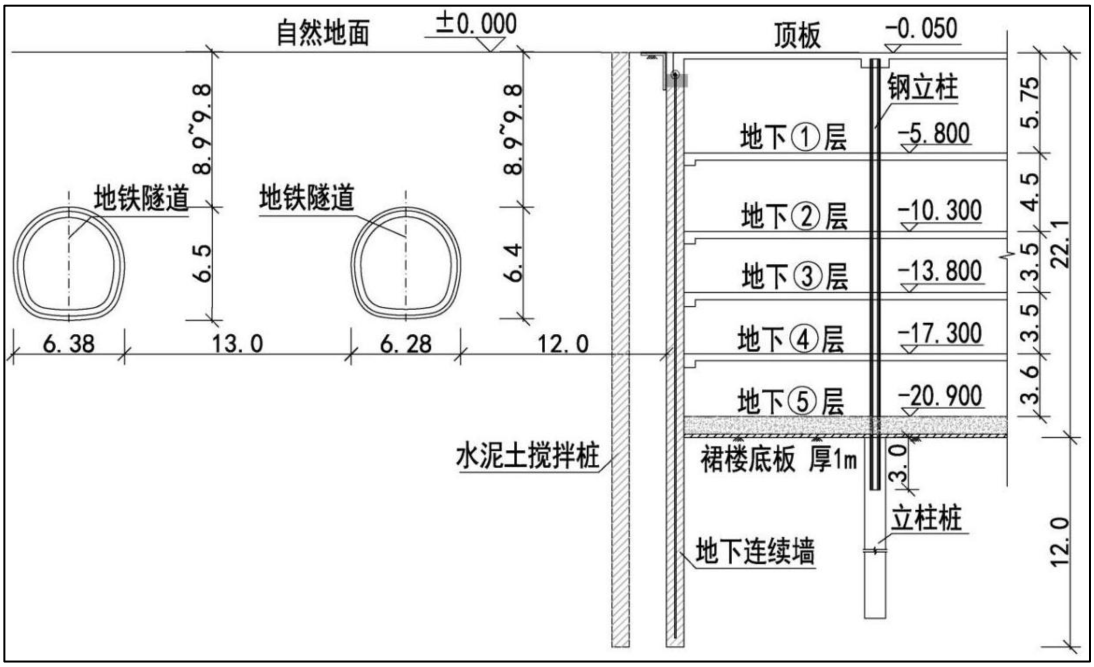

Figure 2. Support Structure Design Profile Adjacent to the Metro Side (units: meters)

4. Analysis of Excavation Impact on Adjacent Metro Tunnel

4.1 Finite Element Model Establishment

The excavation pit has a plan dimension of approximately 170 m × 73 m and a depth of 22.1 m. To account for disturbances to the surrounding soil and the existing metro tunnel, the lateral and bottom boundaries of the model extend to twice the excavation depth. The model dimensions are 270 m × 200 m × 85 m, with mesh refinement in areas prone to stress concentration or significant displacement changes. The mesh is kept as regular as possible to avoid poorly shaped elements, ensuring computational convergence and result accuracy. Boundary Conditions: Lateral sides: Horizontally constrained, Bottom: Fixed, Surface: Free. Material Models: Soil: Mohr-Coulomb (MC) model, Existing metro tunnel: Simulated with plate elements, Diaphragm wall: Simulated with isotropic plate elements, Soil-structure interaction: Modeled using elastic-plastic, no-thickness contact elements (Goodman units). Load Conditions: Construction surcharge: 20 kN/m, with a length equal to the north side of the excavation pit. The 3D finite element model is shown in Figure 3, and the diaphragm wall parameters are listed in Table 1. The excavation simulation is divided into 12 calculation steps, as detailed in Table 2.

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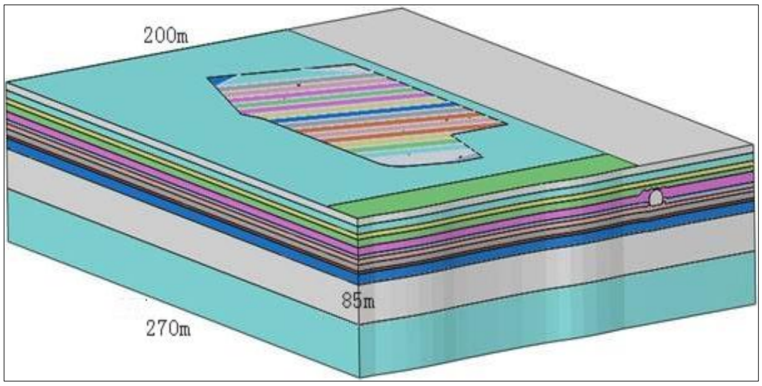

Figure 3. Complete 3D Finite Element Model

Table 1. Diaphragm Wall Calculation Parameters

Parameters	Diaphragm wall
Standard notation for axial rigidity EA/kN·m^{-1}	1.92×10^{7}
Represents flexural rigidity EI/kN·m^{-2}·m^{-1}	1.02×10^{6}
Common symbol for thickness in structural design d/m	1.0
Poisson's ratio ν	0.2
Standard symbol for displacement in mechanics w/kN·m^{-1}·m^{-1}	25

Table 2. Finite Element Analysis Process for Deep Excavation Construction in Nanjing

Phases	Phases process	Phases	Phases process
1	• Construction of triple-axis cement-soil mixing piles	7	• Step 3 excavation to 13.8 m depth
2	• Construction of ring beam and diaphragm wall	8	• Installation of 3rd support
3	• Step 1 excavation to 5.8 m depth	9	• Step 4 excavation to 17.3 m depth
4	• Installation of 1st support	10	• Installation of 4th support
5	• Step 2 excavation to 10.3 m depth	11	• Excavation to pit bottom at 22.1 m
6	• Installation of 2nd support	12	• Installation of base slab

4.2 Excavation Calculation Analysis

4.2.1 Horizontal Displacement of Adjacent Metro Tunnel Sidewall

Since the existing metro tunnel runs parallel to the north side of the excavation pit, the excavation significantly impacts the horizontal displacement of the metro tunnel sidewall. As shown in Figure 4 (displacement contour map of the metro tunnel), when the deep excavation reaches the pit bottom, the maximum horizontal displacement of the adjacent metro tunnel sidewall is 6.24 mm, offsetting toward the excavation pit near the excavation center area. The displacement gradually decreases with distance from the excavation zone, eventually approaching zero.

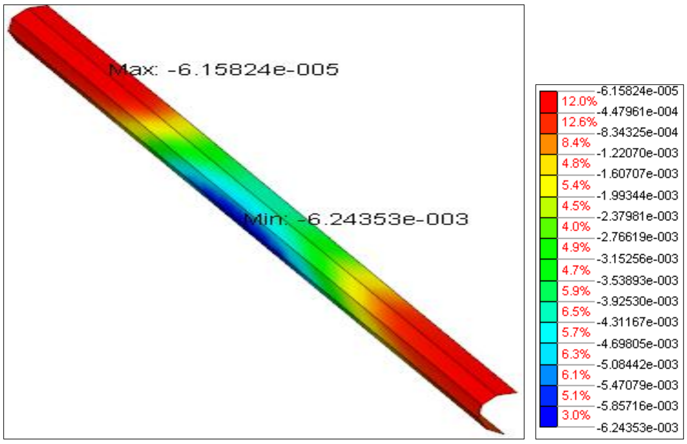

Figure 4. Horizontal Displacement Contour Map of the Metro Tunnel Sidewall (units: meters)

4.2.2 Vertical Displacement of Adjacent Metro Tunnel Bottom

The excavation pit also significantly impacts the vertical displacement of the existing metro tunnel bottom. As shown in Figure 5 (vertical displacement contour map of the metro tunnel), when the deep excavation reaches the pit bottom, the maximum vertical displacement of the adjacent metro tunnel bottom is 6.95 mm, characterized by heave, occurring near the excavation center area. With increasing distance from the excavation zone, the vertical displacement of the metro tunnel bottom gradually decreases, transitioning to settlement.

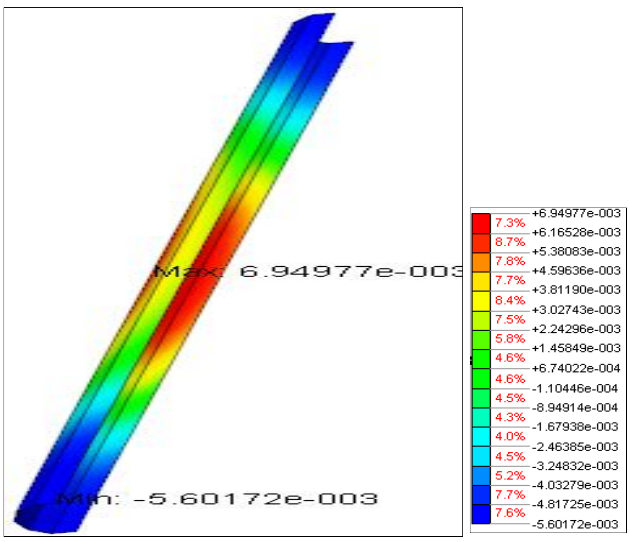

Figure 5. Vertical Displacement Contour Map of Adjacent Metro Tunnel (Unit: m)

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The computational results indicate that the maximum horizontal displacement and vertical displacement of the adjacent metro tunnel both occur near the center of the corresponding excavated pit. As the distance from the excavation area increases, the horizontal and vertical displacements of the metro tunnel gradually decrease.

5. Conclusion

Deep foundation pit engineering imposes stringent environmental protection requirements. To address this, the project implemented reinforcement measures by installing trisaxial cement-soil mixing piles between the diaphragm wall and the metro tunnel. Computational analysis of the retaining structure and adjacent metro tunnel revealed the following: Displacement Patterns: The maximum horizontal displacement of the metro tunnel sidewall and the maximum vertical displacement at its base both occur at the center of the corresponding excavated pit. Displacements (both horizontal and vertical) gradually decrease with distance from the excavation zone. Effectiveness of Reinforcement: The trisaxial cement-soil mixing piles effectively control tunnel deformation, achieving: 2.6 mm reduction in sidewall horizontal displacement 2.8 mm reduction in base vertical displacement. These values comply with the code requirement of ≤20 mm for metro deformation control, validating the rationality of the adopted design measures.

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