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UNVEILING THE SUBTERRANEAN: A NUMERICAL ODYSSEY THROUGH TUNNEL EXCAVATION WITH ABAQUS

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Abstract

The relentless pace of urbanization in China, accompanied by a surge in transportation infrastructure, has intensified the challenges of road traffic congestion. The concurrent development of urban underground facilities, particularly the rapid expansion of urban rail transit, has become a prominent aspect of addressing the escalating traffic concerns. By the close of 2020, an impressive 7,969.7 kilometers of rail transit operation lines were operational in 45 cities, with underground lines constituting a substantial 68.1% of the total length (Figure 1). As of 2021, this trend persisted, with subways commanding a remarkable 78.90% share in the urban rail and transportation operation lines across 9 systems. This paper aims to scrutinize the dynamic landscape of China's urban rail transit system, emphasizing the evolving role of underground lines in mitigating the challenges posed by increasing urbanization and transportation demands. The comprehensive analysis includes an exploration of the development trajectory, operational statistics, and the substantial contribution of subways to the overall urban transit network. The study delves into the implications of this substantial growth, considering the impact on urban mobility, environmental sustainability, and the broader urban landscape. The findings underscore the significance of underground rail transit in the Chinese urban context, not only as a solution to traffic congestion but also as a crucial component of sustainable urban development. As cities continue to grapple with the complexities of transportation management, understanding the patterns and implications of urban rail transit expansion becomes paramount for informed urban planning and policy decisions.

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Introduction

In recent years, due to the rapid development of urbanization level construction in China and the surge in the number of transportation facilities, the road traffic situation has become more and more anxious, urban underground related facilities have emerged, the construction speed of urban rail transit is fast, and the cumulative length of urban rail transit operation lines is also constantly breaking through new highs (Figure 1). By the end of 2020, a total of 45 cities opened 7969.7 kilometers of rail transit operation lines, of which 5422.3 kilometers were underground lines, accounting for 68.1%, and by 2021, as shown in Figure 1, in China's urban rail and transportation operation lines currently operating at the same time in 9 systems, the subway is still the largest proportion, rising to 78.90%.

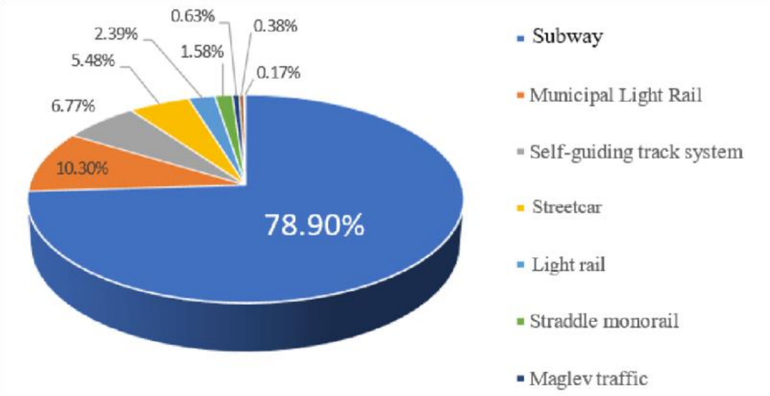

Figure 1: The proportion of urban rail transit operation route structure in China in 2021

Urban tunnel engineering also includes highway tunnels, underground passages, including sewage tunnels, cable tunnels and other comprehensive pipe corridors and other underground facilities, more and more dense underground structures will inevitably have an impact on above-ground buildings, also from the perspective of people's increasingly developing material needs, in the near future, the coverage of above-ground buildings will continue to rise, the construction industry may be organically combined with new building materials, 3D printing and other emerging industries, industries, ushered in the "second spring"[2].Therefore, it is inevitable that underground tunnel excavation will interact with the building. During tunnel excavation, it is inevitable that the soil will be displaced. Whether the soil will have an impact on the existing buildings above during the deformation process will be a safety issue that cannot be ignored.

At present, scholars at home and abroad have conducted in-depth research on the impact of tunnel excavation on the surrounding soil and adjacent buildings. Zhu [3] et al. used ABAQUS system to study the influence of two typical shield construction parameters, grouting pressure and face thrust, on the adjacent multi-layer frame structure. Yu [4], Cao [5] and others used MIDAS to analyze and establish a three-dimensional geological model to analyze building settlement. Guo [6], Zhang [7], Xu [8], Liang [9], Zhao [10], etc. used FLAC3D to conduct numerical simulation, and analyzed and studied the modules of surface settlement, side soil and surrounding strata deformation. Zhang [11] et al. used Peck's formula for numerical analysis, and data processing through Tecplot to analyze the hazard of tunnel construction to the building and the vulnerability of the building itself. Zhu [12, 13], Yang [14], Han [15] et al. used PLAXIS finite element calculation to explore the influence of building foundation position and additional stress on pile anchor support.

In order to explore the influence of tunnel excavation on neighboring buildings, this paper uses Qingdao Metro Line 3 as the engineering basis, and uses ABAQUS software combined with element deletion algorithm, Mohr-Coulomb yield criterion and element tracking method to establish a numerical model. This simulation method provides some guidance and reference for similar projects.

Engineering overview

This paper takes Qingdao Metro Line 3 as the research background (Figure 2). In the Wu-jiang area, from May Fourth Square Station, walk along Hong Kong Middle Road, pass through a number of highrise office and commercial and residential buildings, reach Nanjing Road and follow the road to Jiangxi Road Station. This paper mainly takes this section of the route as the research object, and the size of the excavation section (span × height) of this section is approximately 6.5m×6.5m, composite lining. Combined with the simulation conditions and engineering conditions, the superstructure selected in this paper is the frame structure, the main building is 14 floors above ground, the underground depth is about 9.9m, and the base is about 16m from the tunnel vault [16].

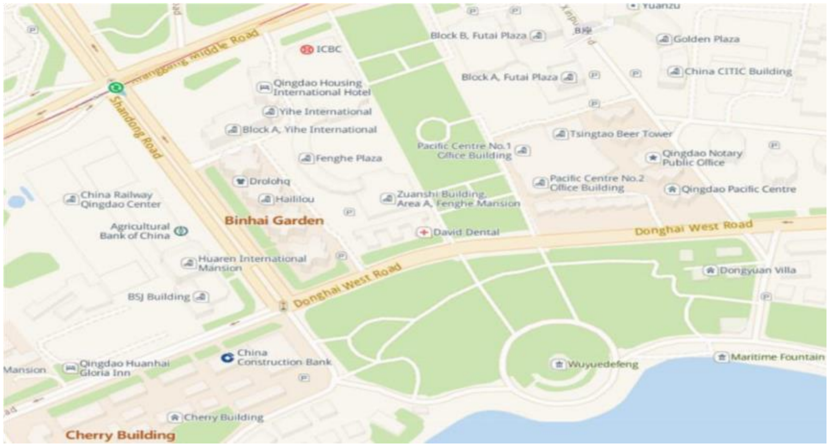

Figure 2: Map around Wusi Square Station of Metro Line 3

Numerical model building

Based on the architectural distribution and engineering characteristics of the study interval, ABAQUS is used to simulate tunnel excavation, and the main process is divided into three steps: (1) the self-gravity stress loading and in-situ stress balance of the rock mass where the tunnel is located are established to simulate the stress distribution state affected by the unexcavated disturbance of the rock mass. (2) The element deletion method in ABAQUS software is used to realize the excavation and lining support effect of tunnel opening. (3) Build the frame structure above the tunnel, and simulate the contact state between the foundation of the frame structure and the soil by the contact method of the built-in interval. (4) Iterative calculations are carried out to analyze the impact of tunnel excavation on existing buildings above.

In practice, the element will disappear due to damage and fracture. To simulate this situation, the ABAQUS software platform provides cell deletion capabilities. In this paper, the direct deletion technology to the element is used to simulate the disappearance of the rock mass in the tunnel entrance area, which is implemented by the *MODEL CHANGE, TYPE=ELEMENT, REMOVE command statements.

Wall rock model establishment

Based on the ABAQUS software platform, a two-dimensional calculation model of interval tunnel and frame structure is established by using the plane stress calculation mode (Figure 3). The size of the wall rock is 100×100m, the density of it is 2350kg/m^3, the elastic modulus E=0.9GPa, the Poisson's ratio μ=0.2, the internal friction angle ϕ=36.5°, and the cohesion C=0.12MPa (Table 1). A total of 7310 wall rock grid elements are divided into structured meshing form, and the mesh type is CPS4R. Since the tunnel section requires focused analysis, its internal mesh is refined again, as shown in Figure 4. The bottom of the model is constrained vertically and both sides are horizontally constrained.

The horizontal constraint on both sides of the soil and the vertical constraint at the bottom simulate the infinite displacement boundary conditions of the soil, and the balance between the self-weight stress of the soil and the initial test stress is considered to simulate the natural stress state of the soil [17]. The wall rock is subject to vertical constraints from the upper soil when there is no building at the top, and vertical loads from the building (soil loads are also included) when there are buildings. The bottom of the model is constrained vertically and both sides are horizontally constrained.

Table 1: Mechanical properties of Wall rock

Wall rock	Density ρ	Elastic modulus E	Poisson's ratio μ	Internal friction angle ϕ	Cohesion C
	2350 kg/m ^{3}	0.9GPa	0.2	36.5°	0.12MPa

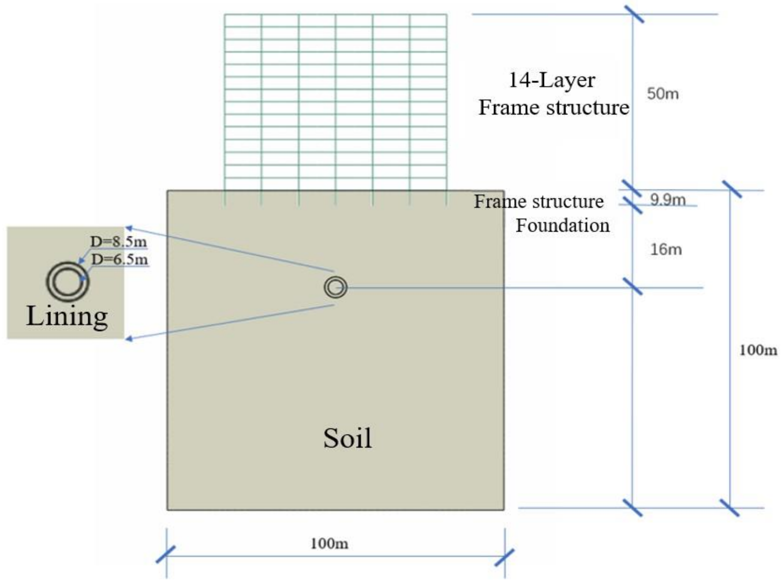

Figure 3: Two-dimensional model of tunnel and existing building

Framework model building

The frame structure model was established using reinforced concrete materials. The frame structure simulation is 50m high and 66.0m long. The cross-sectional properties of beams and pillars are shown in Table 2 below, with a density of 2500Kg/m^3 and an elastic modulus of 30GPa and Poisson's ratio μ=0.2.

Table 2: Frame structure properties

		Beam	Pillar
Section	The element type	Beam	Beam
	Cross-section shape	Square	Square
	Cross-sectional dimensions	0.25*0.5	0.4*0.4
Material	Density ρ	2500Kg/m^3	
	Elastic modulus E	30GPa	
	Poisson's ratio μ	0.2	

Using the Structured grid form, the frame structure is divided into 285 meshes. Once the assembly is complete, this is shown in Figure 4.

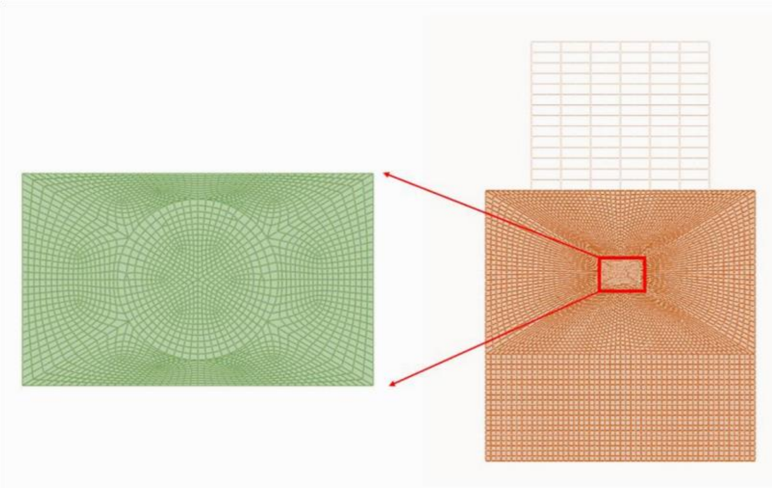

Figure 4: Details of the division of the meshes

Mohr—Coulomb Yield criterion

The wall rock was simulated using a plastic model, using the Mohr—Coulomb yield criterion as follows:

f □ (□1 □□3)□(□1 □□3)sin□□2c□cos□□ 0 (1)

In the above formula, σ_1 is the first principal stress of the elements; σ_2 is the second principal stress of the elements; σ_3 is the third principal stress of the elements; C is the cohesive force; φ is the angle of internal friction.

The principal stress is the solution of equation (2), which is calculated as follows:

□i3 □I1□i2 □I2□i □I3 □0 (2)

In the above formula, I_1 represents the first invariant of the stress tensor; I_2 represents the second invariant of the stress tensor; I_3 represents the third invariant of the stress tensor.

Analysis of the results

Deformation analysis of the tunnel and wall rock

During the tunnel excavation, it can be found that the horizontal displacement of the tunnel shows symmetrical displacement, which becomes more obvious with the excavation of the tunnel, but it is still very subtle and negligible, as shown in Figure 5 below.

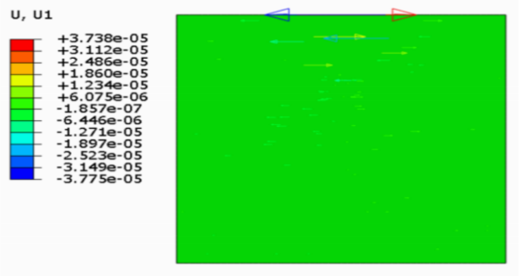

Figure 5(a): Horizontal displacement of the wall rock during excavation

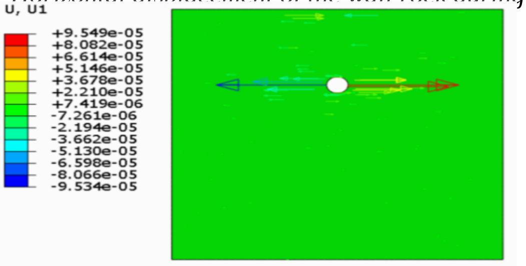

Figure 5(b): Horizontal displacement of the wall rock after excavation

Figure 5: Horizontal displacement of the wall rock

The vertical displacement of the tunnel shows an overall collapse trend during the excavation process, and after the lining installation is completed, the upper wall rock has a tendency to produce upward displacement, and the lower wall rock still has a downward displacement. However, the overall vertical displacement is small and negligible. This is shown in Figure 6 below.

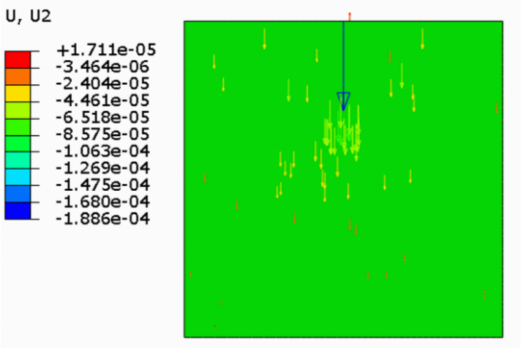

Figure 6(a): Vertical displacement of the wall rock during excavation

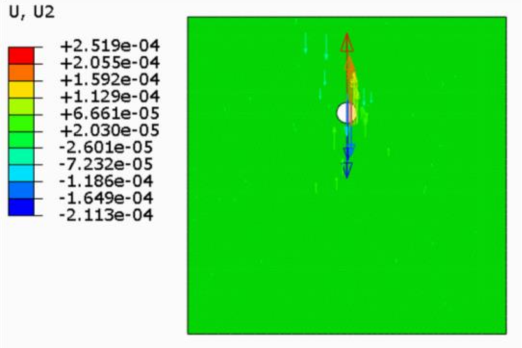

Figure6 (b): Vertical displacement of the wall rock after excavation

Figure 6: Vertical displacement of the wall rock

Force and deformation analysis of frame structure

Through simulation, it is shown that during the tunnel excavation, the superstructure of the upper frame structure shows the deformation settlement of the whole downward and the two sides shrinking to the middle. This is shown in Figure 7 below.

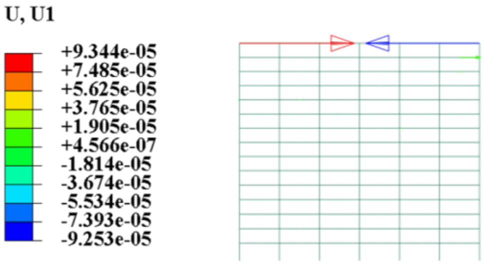

Figure 7(a): Horizontal displacement of the frame structure

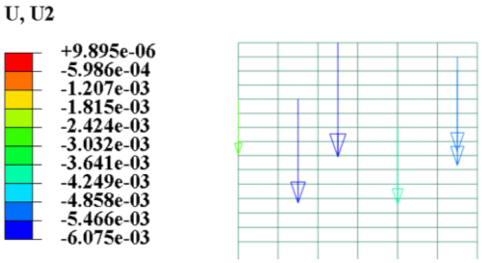

Figure 7(b): The frame structure is vertically displaced

Figure 7: Displacement of the frame structure

Due to the deformation trend of the frame structure, the force at the bottom of the frame gradually increases. As shown in Figure 8 the maximum stress of the bottom of the frame building is reached after the completion of excavation, which is 5.08×10^6Pa. The longitudinal distribution of stress cases is shown as a gradual decrease from the bottom to the top, and the pillar is subjected to greater stress in the lateral distribution.

As can be seen from Figure 9 and Figure 10 below, the settlement of the building above the tunnel is evident with the increase of the floor, and the frame structure in this model has the largest settlement of 6mm at the top 14 floor. According to the actual situation of the project, the settlement of the building is about 5mm. Since this model does not apply support measures such as bolts to the tunnel, the result is large, but it is still within a reasonable range.

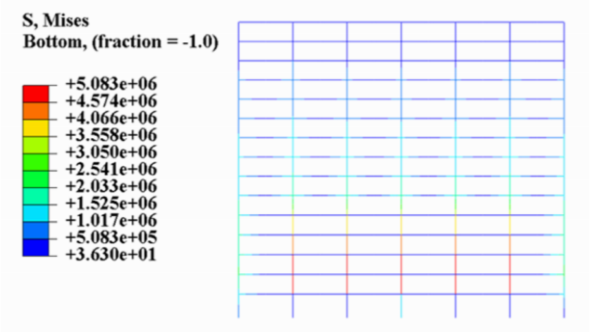

Figure 8: Stress on the frame structure

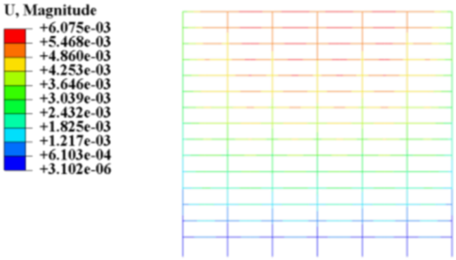

Figure 9: Displacement of frame structure after excavation

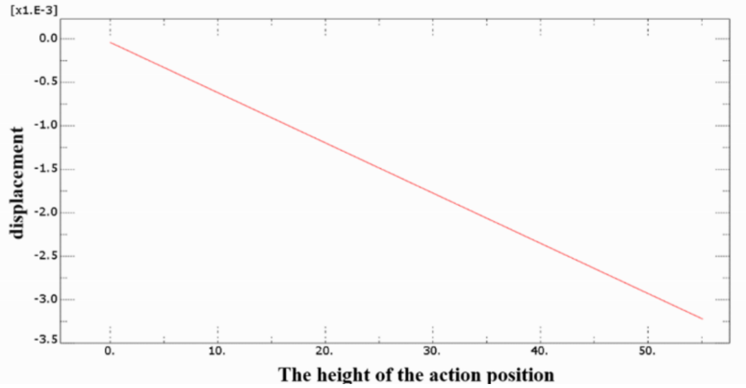

Figure 10: Diagram of the leftmost settlement of the frame structure with height

As shown in Figure 11, the top of the frame structure is horizontally offset under tunnel excavation, but the offset is negligible. In the vertical direction, the displacement at the bottom of the frame structure is small due to the embedded soil, but with the increase of height and the decrease of constraints, the settlement amount gradually increases, and finally the settlement change shown in Figure 12 below is shown at the top of the frame structure, showing the largest settlement amount in the span in each collapse, and the settlement amount at the pillar support is low. And the law of gradual increase of settlement between the two sides in the overall structure, as shown in Figure 13.

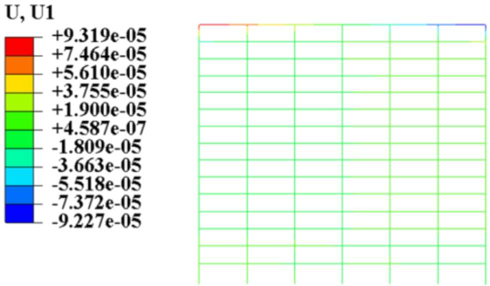

Figure 11: Horizontal displacement of the frame structure

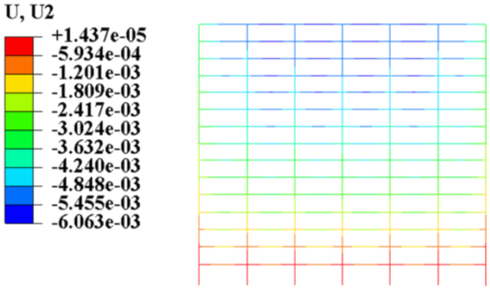

Figure 12: Vertical displacement of the frame structure

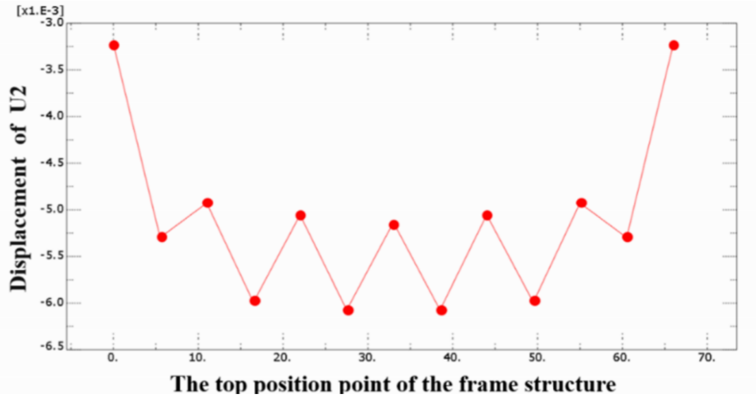

Figure 13: The amount of settlement at the top of the frame structure

In Figure 13, the X-axis is the different positions in the frame structure, and the Y-axis is the settlement amount in the vertical direction at different positions. The chart shows the above pattern.

At present, there is no systematic evaluation standard for the deformation control and prevention of adjacent buildings in tunnel construction. For example, in Beijing, Shenzhen, Shanghai and other places, it is generally stipulated that the surface settlement caused by underground excavation is +1cm (uplift) ~ -3cm (settlement), and it is considered that it does not exceed the limit of this interval. The limit value range is mainly based on expert experience, there is no relevant theoretical basis, and it is a temporary construction control value. The characteristics of this project and the current specifications stipulated [18-20] that the settlement control value of the excavated tunnel under the existing building load conditions was 16.0mm, and the 6mm settlement in the model was within the empirical range, indicating that even if auxiliary measures such as support were not taken in the excavation project of the subway tunnel, the impact on the upper buildings was weak, and the impact was within a reasonable range.

From the simulation results Figure 14, it can be seen that the settlement of the pillars in the frame structure is most obvious in the part where the soil is in contact with the building, that is, the top of the soil mass and the bottom of the building.

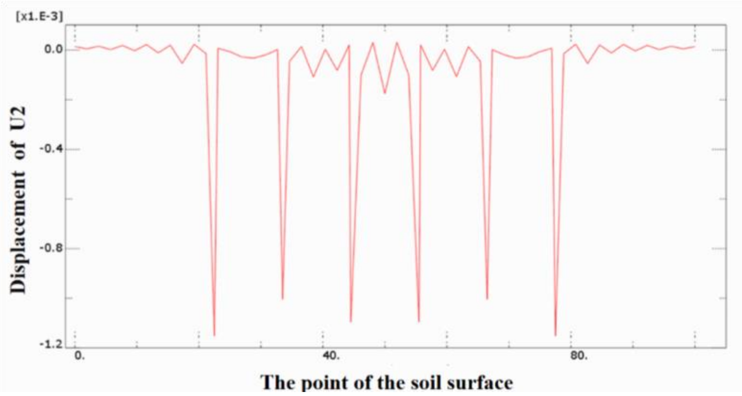

Figure14: The amount of settlement at the bottom of the frame structure

Conclusion

In order to verify the impact of the existing buildings above during the excavation of the subway, this paper establishes a simplified version of the tunnel and upper frame building digital model based on ABAQUS numerical simulation software based on the working conditions of the existing buildings above Qingdao Metro Line 3 and above, using the element deletion algorithm, Mohr-Coulomb yield criterion and element tracking method, and the results are as follows:

(1) Compared with the vertical direction, the horizontal direction of the tunnel, that is, the stress on both sides is greater. In actual engineering, both sides of the tunnel should be reinforced in the presence of existing buildings above.

(2) During the tunnel excavation, the maximum settlement of the existing buildings above is 6mm, which meets the engineering safety requirements and is more in line with the actual situation.

(3) In this paper, a two-dimensional plane stress numerical model is established, but a threedimensional stress numerical model is not established, and the stress change in the tunnel depth direction needs to be further studied. At the same time, other factors that may have an impact during the construction process are ignored, such as the possible soil loss rate during the excavation process[21], which needs to be further analyzed and simulated.

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