Study on the control of construction impacts of shield tunnels in close proximity to sensitive buildings

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Abstract. The construction of interchange passages, which are important appurtenances to metro traffic, often has problem of close proximity to existing buildings. This paper takes the shield excavation project of interchange passage at Jinjiadu Station of Hangzhou Metro Line 2 and Line 4 as an example, and aims to study the impact of shield on existing buildings when crossing them in close proximity. The shield excavation area has a minimum clearance of 1.09 m from the bottom of the station, and the twin tunnel cross a total of six lattice piles with a closest distance of 0.176 m. In order to reduce the impact of the shield excavation on the existing buildings, the excavation area was pre-reinforced with permafrost reinforcement protection measures. A 3D finite element model was built to study the deformation of the existing building under the reinforcement measures. By studying the key construction parameters, the results show that in this project a smaller Propulsion pressure and grouting pressure and a larger grouting volume can effectively reduce the impact of construction on the existing building.

1. Introduction

With the rapid development of regional economy, the demand for reliable transport and infrastructure in urbanised regions is increasing. As a regional transportation tool, metro can effectively meet the travel demand. The metro passageway, as an annex to the metro operation, provides a convenient interchange for passengers. It is worth noting that the metro passageway is characterised by close proximity to existing building construction and therefore changes the stress and displacement fields of existing buildings and piles during the new construction process [1]. Underground tunnels are usually excavated using the shield method, so the engineering nature is same as close tunnelling through existing buildings. Currently, the main research for existing buildings and new tunnels is to obtain frictional resistance, settlement and relative deflection of the building pile structure after tunnel crossing by experiments or numerical simulations [2-4]. In terms of surface settlement, it has been shown that the surface settlement caused by twin tunnel excavations is not a simple superposition of two Gaussian curves, but is mainly caused by the interaction between the tunnels [5-9]. As the close crossing of existing buildings have a large impact on the structure, the natural soil in the danger zone is usually converted to permafrost to improve the soil stiffness and reduce soil disturbance to a certain extent [10]. To better reduce the impact of crossing construction on existing buildings, Einstein and Ocak et al. found that construction parameters such as working face pressure, infiltration rate, grouting pressure and fill rate had a significant effect on settlement [11-14]. In the above-mentioned studies, there is limited research on the construction parameters for close underpassing of existing works under freezing method reinforcement measures. Based on the above-
mentioned engineering background, this paper analyses the rationality of freezing reinforcement measures by means of numerical modelling and investigates optimisation options based on measures of propulsion pressure, propulsion speed, grouting pressure and grouting volume as a means of reducing the impact on existing buildings.

2. Engineering background and control standards

2.1. Overview of the project
The case study of this paper is the new construction of two parallel interchange tunnels between Hangzhou Metro Line 4 and Jinjiadu Station of Line 2. The tunnels are 31 m long and the top of the tunnels cross the bottom slab of Line 2 station at almost zero distance. The outside of the tunnel on the left and right lines will have to cross six lattice piles of Line 2 stations, four on the left line and two on the right line. The plane relationship diagram is shown in Figure 1. The left line tunnel has a minimum clearance of 17.6 cm from the lattice piles, while the right line tunnel has a minimum clearance of 31.6 cm, thus requiring a high level of disturbance control. The tunnel was completed by a Φ 6380 earth-balanced shield in both directions, starting with the left line and then the right line. The inner diameter of the liner is 5500 mm, the outer diameter of the liner is 6200 mm, the width of the liner is 1200 mm and the concrete strength of the liner is C50.

![Figure 1. Interchange crossing project level plan.](image1)

![Figure 2. Schematic diagram of the shield crossing the strata.](image2)

2.2. Geology
The shield crosses stratum as shown in the Figure 2, the new tunnel mainly crosses intervals 6 and 7. 6 layer has high compressibility, low strength, high sensitivity, easy to produce rheological and thixotropic changes. The shield initiation and reception areas are reinforced with "cup" shaped freezing wall. The effective thickness of freezing wall is 2.5 m for the "cup base" and 1.5 m for the "cup wall". The average temperature of freezing wall is -10°C.

2.3. Engineering control standards
Tunnelling close to existing buildings will increase the settlement and bending loads on piles and existing buildings. According to the Railway Line Maintenance Rules and related design requirements, the control criteria caused by this project during construction are shown in Table 1.

| Station | Lattice pile | Surface settlement |
|---------|--------------|-------------------|
| Vertical displacement (mm) | ±5 | 5 | ±8 |
| Horizontal displacement (mm) | ±5 | 5 |

3. Numerical models
The mechanical behaviour of soil during the forward excavation and jacking of the shield machine in tunnel construction is complex and this paper will establish the entire analysis process under reasonable conditions to reduce the impact of uncertainty on the study.
3.1. Model Overview

Combined with the actual engineering situation, finite element software was used to establish a refined model of the Jinjiadu Line 2 station and its nearby strata. The model space size is 150.0 m × 31.2 m × 41.4 m in length × width × height, and model details are shown in Figure 3. In this paper, the simulation is combined with actual engineering situation, and some areas of existing building are modelled with reasonable simplification, for example: (1) Simulating the existing station structure with plate units; (2) Ignoring the influence of operating metro on the tunnel excavation; (3) Ignoring the inhomogeneity of the freezing method. In the simulation, the time effect of soil deformation is not considered during shield advancement.

![Figure 3. Numerical model schematic.](image)

3.2. Material parameters

Mohr-Coulomb constitutive model can still be well applied to numerical calculation under complex conditions [15], and in this paper, the Mohr-Coulomb principal is used to establish the soil layers in the modelling, where the relevant parameters of each soil layer are detailed in Table 2. All materials are isotropic materials.

| Stratum                   | K₀   | γ (kN/m³) | Eᵣ (MPa) | μ     | C (kPa) | φ (°) |
|---------------------------|------|-----------|-----------|-------|---------|-------|
| Mixed backfill            | 0.47 | 18.5      | ( - )     | 0.33  | 10.0    | 16.0  |
| ⑤1 silty clay             | 0.38 | 19.3      | 5.8       | 0.28  | 40.5    | 15.5  |
| ⑤2 sandy clay             | 0.43 | 18.6      | 5.5       | 0.3   | 2.0     | 20.0  |
| ⑥2 muddy-silty clay       | 0.56 | 17.8      | 2.7       | 0.36  | 14.0    | 10.5  |
| ⑦1 silty clay             | 0.37 | 19.1      | 6.2       | 0.27  | 53.0    | 17.0  |
| ⑧1 silty clay             | 0.39 | 19.2      | 6.0       | 0.28  | 50.0    | 17.0  |

3.3. Numerical calculation procedures

The whole shield tunnel construction can be roughly regarded as four cycle processes: shield machine excavation, shield machine advance, shield tail grouting and segment assembly, so as to study the disturbance law of shield tunnel construction on soil and existing buildings. The excavation of the twin tunnel was completed in 26 steps. The main steps are as follows.

(a) Obtain the initial ground stress equilibrium state of the model under self-weight, and clear the displacement.

(b) Use the function of life and death unit and unit tracking to excavate the soil within the diameter of shield machine. A pressure load is applied to the excavation surface to simulate the support of tunnel face. Set the load release coefficient combination to simulate the supporting effect of shield machine.
(c) The grouting pressure and release coefficient are applied on the surface of surrounding rock unit to simulate the grouting process of shield tail.
(d) The grouting pressure on the confining pressure surface is removed within a certain range of the shield tail, and the lining and grouting layer are established to simulate the assembly of the shield tail tube and the grout hardening process.

4. Analysis of impact results under recommended working conditions

The simulation is carried out with a propulsion pressure of 450 kPa-550 kPa, a stress release coefficient of 0.3+0.7, a grouting pressure of 230 kPa, and a grouting pressure attenuation coefficient of 1-0.6 as standard parameters. The final surface settlement simulation results of the two tunnels are shown in Figure 4. After the construction is completed, the maximum surface settlement is 4.71 mm, which meets the design requirements. After the excavation of the second tunnel was completed, the uplift of the first tunnel was further intensified, and a belt-shaped settlement trough was formed between the two tunnels. Due to the existence of the Line 2 station, the overall uplift of the ground surface is not large, and there is no obvious peak.

Assuming that the observation point is the closest to the new tunnel from the lattice pile, the horizontal displacement of the lattice pile is shown in Figure 5. Due to the existence of reinforcement measures, the horizontal displacements of the six post piles are all within the design range. The soil compression caused by the excavation of the two tunnels caused the lattice pile to move outward, and the horizontal displacement of the pile increased rapidly during the traverse period, and the horizontal displacement of the lattice pile was inversely proportional to the distance between the lattice pile and the tunnel. The lattice pile b and c will have a secondary displacement when the tunnel passes through the next group of lattice piles a and d, and the displacement is relatively large. Certain measures are needed to reduce the secondary displacement of the pile b and c during construction.

![Figure 4. Surface settlement.](image1)

![Figure 5. Horizontal displacement of lattice pile.](image2)

Figure 6 shows the horizontal displacement of the existing station floor, as most of the tunnel crossing area at the bottom of the station is reinforced by freezing method, the unreinforced area of the existing station floor has a small horizontal displacement, while the reinforced area floor will have a slightly larger horizontal displacement due to freezing.

![Figure 6. Horizontal displacement of existing station.](image3)

5. Sensitivity studies on construction parameters
During the tunnel construction process, the existing subway stations are operating as usual, and the stability of the soil layer of the tunnel vault is relatively poor. Therefore, the micro disturbance of the environment has a great impact on the section. After the construction of the first ring segment is completed, the cumulative value of the single ring uplift of the station and the lattice pile shall not exceed 0.3 mm, which is used as the sensitivity judgment standard for the construction parameters in the study. By studying the influence of construction parameters on the final settlement of the lattice pile and the station, it is possible to reduce the impact of construction on existing buildings as much as possible while meeting the safety of the project.

5.1. Propulsion pressure impact analysis

The propulsion pressure determines the disturbance of the front soil by the shield. The propulsion pressure $T$ of the working face can be determined by the static earth pressure formula $T=k \sigma_z$, where $k$ is the coefficient between the propulsion pressure and the static earth pressure. Taking $k$ as 0.8, 1.0, and 1.2 for the study, the propulsion pressure of the face is 350-450 kPa, 450-550 kPa, 550-650 kPa, respectively.

It can be seen from Figure 7 that as the propulsion pressure increases, the six lattice piles all show an upward displacement trend. When the shield machine is advancing, the upward displacement of the pile b, c and e, which is not protected by frozen soil reinforcement, will increase greatly with the increase of the propulsion pressure, and the maximum increase is 0.43 mm. It can be seen from Figure 8 that after the excavation of the two tunnels is completed, the smaller propulsion pressure can effectively slow down the growth rate and the amount of the station uplift, and the maximum reduction is 0.3 mm. The freezing and strengthening of the soil layer increases the strength of the soil, so the propulsion process of the shield in the frozen soil has a lower impact on the surrounding soil. It can be seen that the propulsion pressure is one of the important factors affecting the construction quality, and 350-450 kPa should be used as the main propulsion pressure value in this project.

5.2. Propulsion speed impact analysis
The rate of propulsion determines the rate at which the pipe sheet receives soil pressure, and this paper simulates the rate of propulsion by means of pressure release coefficients. Based on the pre-designed propulsion speed, combined with the model propulsion step, pressure release factors of 0.2+0.8, 0.3+0.7 and 0.4+0.6 were selected in the study. Figure 9 shows that the propulsion speed has little effect on the station, and a smaller propulsion speed can reduce the station uplift. Figure 10 shows that the upward displacement of the lattice piles a, b and c increase with the increase of the propulsion speed, and the upward displacement of the other lattice piles has not changed significantly. Too fast propulsion speed makes it more difficult to control the attitude of the shield, and there may be a risk of pile cutting. Due to the soft soil layer, a lower propulsion speed is required to reduce the risk of pile cutting.

5.3. Analysis of the effect of grouting pressure

Grouting pressure is one of the most important parameters in shield tunnelling and is studied in this paper for three cases with a grouting pressure of 200 kPa, 230 kPa and 250 kPa respectively. Different grouting pressures have no significant effect on the upward displacement of the lattice pile in the unreinforced area. The main reason is that the softer soil layer will reduce the influence of the grouting pressure on the piles. Figure 11 shows that the grouting pressure has a greater influence on the upward displacement of the pile a, d and e, which is mainly because the three piles are in the reinforced area, so the larger grouting pressure will destroy the reinforced soil layer. It is worth noting that Figure 12 shows that the uplift of the bottom of the station in the reinforced area increases significantly when the grouting pressure increases, and the maximum increase is 0.86 mm. It can be seen that the grouting pressure is also one of the important parameters that affect the construction quality. During the construction process, a smaller grouting pressure needs to be applied to the reinforcement area to reduce the impact of excavation on existing buildings.

5.4. Analysis of the effect of grouting volume
The amount of grouting determines the solidification time of the grout and the residual pressure after the pressure is attenuated. During tunnel construction, the amount of grouting needs to be controlled according to the geological and construction conditions. In this paper, the pressure attenuation coefficient is used to simulate the size of the grouting volume, and the pressure attenuation coefficients are respectively 1-0.4, 1-0.6 and 1-0.8 for research.

The increase of grouting volume has little effect on the upward displacement of lattice piles, and the upward displacement of lattice piles will slightly increase with the increase of grouting volume. Figure 13 shows that when the amount of grouting increases, a larger amount of grouting can effectively slow down the uplift of the existing station floor, and the overall bottom uplift is relatively flat. The main reason is that the twin tunnel is excavated in a narrow space. A large amount of grouting can effectively reduce the stress release caused by soil loss, thereby reducing the uplift of the station. This means that a larger grouting volume is more suitable for this project.

6. Conclusion
In this paper, a three-dimensional finite element model of the underground interchange twin passages of Hangzhou Metro Line 2 and Line 4 Jinjiadu Station is established to study the impact of the new twin tunnel underpass and side passages on existing buildings. The main findings of the study are as follows.
(a) Under the freezing method of reinforcement, the maximum surface uplift caused by the construction of the new twin tunnels through the bottom of the existing station was 4.71 mm. The horizontal displacement of the lattice piles of the existing station and the horizontal displacement of the station floor were both small and in accordance with the design requirements.
(b) During the traversal of the lattice piles, the horizontal displacement of the later traversed lattice piles will occur earlier due to the soil compression caused during the earlier traversal of the lattice piles and will reach its maximum at the end of the traversal.
(c) In this project, the impact of the new tunnel on the existing buildings can be effectively reduced by varying the propulsion pressure and grouting pressure values. According to the numerical simulation results, a propulsion pressures of 350-450 kPa and a grouting pressure of 200 kPa are more suitable for this project. At the same time, a lower propulsion rate and a higher grouting volume within the safety limits can ensure better quality of work.

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