Pile Active Underpinning of Existing Building Foundation with Undercrossing Shield Construction

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Abstract. Undercrossing shield construction of a subway, the tunnel vault is about 3.0m away from the foundation pile tip of the existing building. In order to analyze the influence of shield undercrossing construction on the existing building and the influence of the existing building load on the tunnel structure, the calculation and analysis are carried out for the existing foundation forms, foundation reinforcement into raft, addition of equal length piles and increase of unequal length piles. Using the method of foundation reinforcement into raft foundation and long pile tip exceeding 0.5m below the tunnel floor can transmit the load of the upper building structure to the soil layer below the tunnel floor and reduce the load of the tunnel roof, thereby achieving the underpinning effect. According to the allowable deformation value of existing building, allowable internal force of segment and allowable deformation value of segment, using this underpinning method can meet the requirements of the various of allowable values of existing building, tunnels, etc.

1. Foreword
As more and more subways appear in the city, lines of subway are inevitably undercrossing the existing building, causing problems such as surface settlement and building cracking during the construction of shield[1-4], which also causes concern.

When there is existing building above the shield, additional stress will be generated in the foundation soil, which will affect the construction and operation of the subway. Zhang Hongbin et al[5] analyzed a project about the large-scale commercial and residential building above a certain section of the Guangzhou Metro. After the subway operating, the segments of the tunnel double-line shield section showed cracking and falling off. Zhang Yazhou et al[6] pointed out that when the shield passes through the residential building, the overloading of the residential building should be taken into account, and the mud pressure setting should be set by “resting earth pressure + water pressure + preload + overload preload” to reduce later settlement of the soil. Yan Kai et al[7] studied the surface settlement caused by shield undercrossing piles and the law of pile body stress: the tunnel vault is 9m away from the pile tip, and the maximum of surface settlement is biased to the side where the bridge pier with larger load, indicating that even the tunnel vault is 9m away from the pile tip, the construction of undercrossing
shield still affects the upper structure. Guo Yuancheng et al. [8], through numerical simulation, concluded that the closer the distance between the pile tip and the tunnel vault, the greater the vertical settlement of the pile foundation, as well as the larger the loss of bearing capacity. And the negative frictional resistance may occur at the bottom of the pile body, which seriously affects the bearing capacity of the pile foundation of the upper structure.

The influence of shield construction on existing building can be controlled by means of reducing surface settlement. In terms of shield construction technology, the construction parameters of the shield can be adjusted to reduce ground loss and reduce settlement [9-12]. If the shield vault is relatively close to the existing building foundation, the influence of the existing building structure cannot be avoided by adjusting the construction parameters, and active reinforcement underpinning is required [13-14].

The thing referred to here is called active underpinning, which refers to the reinforcement and underpinning on existing building before the undercrossing shield construction, and it is carried out by strengthening the foundation. The characteristic is that, by reinforcement and underpinning, the safety of the existing building can be ensured, and the adverse effects of the existing building load on the tunnel segments structure will not interfere with the normal operation of the segment.

This paper takes a project as a background to analyze the impact of shield construction on the main body of the building, the influence of the existing building on the tunnel segments, and the measures of reinforcement and underpinning to protect the existing building when the tunnel vault is close to the existing building foundation.

2. Engineering background
The rail transit line 3 of a certain city, crosses a commercial and residential building (the bottom is a shopping mall). The mileage range is right DK12+926~DK12+982, left DK12+941~DK13+010, the undercross length of the right line is 56m, and the left line is 69m. The section is constructed by the shield method, and the left and right lines are both excavated by the Earth Pressure Balance Shield Machine.

The commercial and residential building is an 8-story frame structure with an area of 1,850 square meters (each floor). It was built in the 1990s and has an old appearance. The foundation is the rammed-pile foundation with an independent cap under the column. The length of pile is 13.2 meters. The relative position of the pile tip and the tunnel vault is shown in Figure 1 (the unit is m in the figure), and the pile tip is 3.24m away from the tunnel vault.

![Figure 1. Relative position of the pile tip and the tunnel](image)

3. Calculation and analysis
In order to reduce the impact of the undercrossing shield construction on the commercial and residential building (to ensure the normal use of commercial and residential building), and to reduce the impact of
the existing commercial and residential building on the tunnel segments, a comprehensive calculation and analysis for the tunnel undercrossing is carried out. The calculation scheme is divided into four working conditions: the existing state and the reinforcement state (two states but four working conditions).

The first state is the undercrossing shield construction of foundation without reinforcement (existing state, undercrossing shield construction). Analyze the impact of the undercrossing shield construction on the main body and the impact of the main body on the tunnel structure when there is no reinforcement.

The second state is the undercrossing shield construction of foundation with reinforcement (after the foundation cap is reinforced as a more integral raft and the pile is added, undercrossing shield construction). Analyze the impact of the undercrossing shield construction on the main body and the impact of the main body on the tunnel structure when using the reasonable reinforcement measures.

There are two aspects of reference in the check of the calculation result. The first one is the impact degree of the tunnel construction process on the main building, which is according to the deformation requirements of the building in Table 1[15]. The allowable deformation of the building under the undercrossing shield construction should meet the requirements of Table 1. The second one is that the force and deformation of the tunnel segment structure should meet the design requirements of Table 2.

Table 1. Building deformation control requirements

| Allowable deformation of the foundation | Allowable deformation of the building |
|----------------------------------------|--------------------------------------|
| the settlement difference of adjacent column base is 0.002L (L is the center distance of the adjacent column base) | 15mm |
| the overall inclination of the multi-storey building is 0.003 | 0.003 |

Table 2. Tunnel segment structure control requirements

| Allowable bending moment of the segments /(kNm/m) | Allowable axial force of the segments /(kN/m) | Allowable deformation of the segments /mm |
|-----------------------------------------------|--------------------------------------------|-----------------------------------------|
| 266                                           | 958                                        | 18                                      |

3.1. Calculation model

In order to study the impact of shield construction on 8 floors of existing building and the impact of the pile foundation (close to the tunnel vault) on the tunnel, the PlaxisV8.2 finite element software was used for calculation and analysis. Ma Hailong[16] used that finite element software to calculate the excavation and unloading. The calculation results are consistent with the actual engineering, which indicates that the calculation analysis method is suitable for the excavation and unloading of tunnel.

The Mohr-Coulomb model is used for the soil, and the parameters of the foundation soil are shown in Table 3. The pile foundation is simulated by point-to-point bolt unit, and the foundation is simulated by plate unit with a thickness of 600mm and concrete of C30 strength grade. The tunnel segments are simulated by plate unit with a thickness of 300mm and concrete of C50 strength grade. The calculation parameters are shown in Table 4. According to the existing building state, the building load is determined. And then the PKPM is used to form the load of the pile bottom. After conversion, the design value of the internal column load is 902kN/m, and the design value of the external column load is 480kN/m.

Table 3. Soil Parameter Table

| Number | Name of soil layers | Thickness of soil layers/m | $\gamma$(kN•m$^{-3}$) | $E$/MPa | $c$/kPa | $\phi$ (/°) |
|--------|---------------------|----------------------------|------------------------|---------|---------|------------|
| 1      | Fill                | 3.5                        | 18.0                   | 10.0    | 15.0    | 12.0       |
| 2      | Silty Clay          | 11.5                       | 18.8                   | 15.0    | 14.0    | 12.0       |
| 3      | Silty-fine Sand     | 3.5                        | 19.0                   | 36.0    | 5.0     | 25.0       |
| 4      | Silty-fine Sand     | 11.5                       | 19.5                   | 54.0    | 1.0     | 30.0       |
Table 4. Component Parameter Table

| Number | Name of components | Name of units       | Section size/mm | EA/kN    |
|--------|-------------------|---------------------|-----------------|----------|
| 1      | Pile              | Point-to-point bolt | 250             | 1.000E7  |
| 2      | Baseplate         | Plate unit          | 600             | 5.400E7  |
| 3      | Tunnel Segments   | Plate unit          | 300             | 1.0354E7 |

The classification of calculation working conditions is shown in Table 5. The foundation form of different working conditions is shown in Figure 2.

Table 5. Description of working conditions

| Working conditions | Description of working condition                                      |
|--------------------|---------------------------------------------------------------------|
| Working condition 1 | existing state(without reinforcement)                              |
| Working condition 2 | reinforce the cap as a raft                                         |
| Working condition 3 | reinforce the cap as a raft + add the piles of the same length around the existing piles |
| Working condition 4 | Reinforce the cap as a raft + add long and short piles around the existing piles |

Figure 2. Foundation form of different working conditions
Figure 2a is a calculation model diagram of the undercrossing shield construction in the existing state (no reinforcement measures are applied to the main body of existing building); Figure 2b is a calculation model diagram of the undercrossing shield construction when the cap is reinforced into an integral raft; Figure 2c is a calculation model diagram of the undercrossing shield construction when the cap is reinforced into an integral raft and the piles are added among the existing piles (the altitude of the added piles tip is the same as the existing piles tip); Figure 2d is a calculation model diagram of the undercrossing shield construction when the cap is reinforced into an integral raft and some long and short piles are added to among the existing piles (the altitude of the short piles tip is the same as the existing piles but the long piles tip are 0.5m below the tunnel bottom).

3.2. Calculation and analysis

The main controlled calculation results and corresponding allowable values for the four working conditions are listed in Table 6.

| Working conditions | ε₁/ε₂ (mm) | Building calculated overall inclination/allowable inclination | Segments calculated bending moment/allowable bending moment (kN·m/m) | N₁/N₀ (kN/m) | ε₂/ε₀ (mm) |
|--------------------|------------|------------------------------------------------------------|---------------------------------------------------------------|--------------|------------|
| 1                  | 18/15      | Building calculated overall inclination/allowable inclination | Segments calculated bending moment/allowable bending moment (kN·m/m) | 276/266      | 913/958    | 25/18     |
| 2                  | 0.0000/0.003 | 259/266                                                  | 900/958                                      | 24/18     |
| 3                  | 0.0000/0.003 | 226/266                                                  | 893/958                                      | 23/18     |
| 4                  | 0.0003/0.003 | 204/266                                                  | 774/958                                      | 17/18     |

*ε₁/ε₂ is inter-column calculated deformation/allowable deformation
*N₁/N₀ is segment calculated axial force/allowable axial force
*ε₂/ε₀ is segment calculated deformation/allowable deformation.

There are four control indicators for each working condition. The control indicators of working condition 1 are the deformation between commercial and residential building’ columns, the bending moment, the axial force and the deformation of the segments. The control indicators of working condition 2,3,4 are the overall inclination of the commercial and residential building, the bending moment, the axial force and the deformation of the segments.

The calculation results show that the working condition 1: the deformation between the columns is larger than the allowable value, the bending moment of the segments is larger than the allowable value, and the deformation of the segments is larger than the allowable value; working condition 2,3: deformation of the segments is larger than the allowable value; working condition 4: four control indicators all meet the requirements.

4. Analysis of reinforcement and underpinning scheme

It is known from Table 6 in Section 3.2 that in the undercrossing shield construction of the existing state, the three control indicators are larger than the allowable value. So the tunnel undercrossing construction cannot be directly implemented.

Reinforce the cap as a raft, and carry out the tunnel undercrossing construction. However the deformation of the raft is quite large, the calculated bending moment and axial force of the segments are close to the allowable value, the degree of safety is not high, and the deformation of the segments is larger than the allowable value, this reinforcement and underpinning method cannot be adopted.

Reinforce the cap as a raft + add the piles of the same length around the existing piles, and carry out the tunnel undercrossing construction. Because the deformation of the segments is greater than the allowable value, this method should not be used.
Reinforce the cap as a raft + add long and short piles around the existing piles. Because the long piles transfer part of the load of the existing building to the soil layer below the bottom of the tunnel, the load of the tunnel vault is unloaded, and the internal force and deformation of the tunnel segments are reduced. If carry out the tunnel undercrossing construction at this time, the four control indicators can all meet the requirements.

After calculation and analysis, it is finally determined that the reinforcement and underpinning case is implemented by the reinforcement scheme in working condition 4.

It can be seen from above that the concept of underpinning and reinforcement is different. Reinforcement refers to the strength of the object to be reinforced, while the underpinning is carried out by load transfer, so that the applied load can be dispersed and reduced. Therefore, from the concept of active reinforcement underpinning, only the scheme of working condition 4 is the true reinforcement and underpinning.

5. Conclusion
By analyzing the shield of undercrossing construction which is close to the foundation of the building on the ground, the following conclusions are obtained:

(1) In the undercrossing shield construction which is close to the foundation of the existing building, the impact of two aspects should be considered. First, the impact of the undercrossing shield construction on the existing building on the ground. Second, the impact of the load of existing building on the strength and deformation of the tunnel lining segments.

(2) For the protection of building which is close to the undercrossing tunnel and tunnel structures, it should not only adopt the traditional foundation reinforcement method, but also consider the use of the underpinning mainly. The load of the upper building structure is transmitted through the pile body to the soil layer below the tunnel floor, and the roof of the tunnel is unloaded, thereby achieving the underpinning effect.

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