Study on construction technology of metro tunnel under a glass curtain wall

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Abstract. To ensure the safety of the glass curtain wall building above loess tunnel and get an optimal scheme, an elastic-plastic FEM model is established to simulate three reinforcement schemes based on a tunnel section in Xi’an Metro Line 3. The results show that the settlement value of the optimal scheme is reduced by 69.89% compared with the drainage measures, and the uneven settlement value is reduced by 57.5%. The construction points, technical processes and technical indexes of the optimal scheme are introduced. According to the actual project, the cumulative settlement of the building under construction is 16mm, which meets the control standards. According to the actual project, the cumulative settlement of the glass curtain wall building is 16mm, which meets the control standards. The reinforcement scheme can provide some reference for the design and construction of the metro in loess area.

1. Introduction
Historically, due to its less interference to the road, large amount of transportation and land saving, metro has made rapid progress in urban traffic construction. It is an unavoidable special condition to put the existing tunnel under the existing building because of its lines are usually planned in densely populated, large flow of busy areas. The building lot will be disturbed by tunnel construction with varying degrees, which may trigger stratum deformation, and even induce surface subsidence, pipeline damage, building wall cracking and other engineering disasters. Serious economic losses and adverse social impacts will be caused. Therefore, adopting reasonable construction method to excavate tunnel and ensuring the safety of building have great engineering significance.

At present, domestic and foreign scholars have carried out lots of researches on the impact of subway construction and surrounding environment. Karakus et al. used back analysis method to investigate the stratum deformation regularity and stress redistribution caused by tunnel construction[1]. Loganathan et al. explored and forecasted the ground deformation triggered by tunnel construction in cohesive soil layer[2]. Fernando studied the ground subsidence caused by tunnel construction in sandy gravel stratum[3]. He et al. researched the influence of the excavation tunnel construction on the surface of densely populated houses and obtained the optimal excavation strategy by numerical simulation calculation[4]. By analyzing the measured deformation data of masonry structures under 6 subway tunnels in Beijing, Sun et al. summarized the effect of deformation on the basis of masonry structure building settlement construction caused by metro construction[5].

Large amount of useful experience for the influence of the subway on the surrounding buildings and settlement monitoring methods has been accumulated by above researches, but due to the complexity and particularity of practical engineering, the grouting reinforcement measures of the loess tunnel
underneath exiting building are rarely studied. In view of this, to get the best construction plan and implement it, Xi’an Metro Line 3 interval is taken as an example and two dimensional elastoplastic model is established to analyze the stability of buildings under different strengthening conditions. By monitoring analysis, settlement meets the control standard, the measures are proved to be reasonable and effective, some reference can be provided for similar projects.

2. Context
The route trend of Xi’an Metro Line 3 Changtong interval (Changle Park station to Tonghuamen station) is north-south, which passes through the Xi’an Technological University, Golden Flower Hotel and other densely populated areas. The Xi’an No. 4 ground fissure is near the Tonghuamen station, therefore, the concealed excavation method is adopted. The piston ventilating shaft is installed at the entrance of Golden Flower Hotel and the west side of Changle Bridge. The right line is designed to be 42.55m×14.6m which is two floor open structure underground. The tunnel between open structure and Tonghuamen station is 9.68m. The left line is designed to be 12.8m×11.47m large cross concealed tunnel and is used as shield translation well. The tunnel between large cross concealed tunnel and the Tonghuamen station is 39.3m, the tunnel is underneath the glass curtain wall of Xi’an Golden Flower Hotel (figure 1).

![Figure 1. Relationship between the tunnel and the plane position of Golden Flower Hotel building.](image1)

![Figure 2. The relationship between the tunnel and vertical section of Golden Flower Hotel building.](image2)

The upper part of Golden Flower Hotel belongs to frame shear wall structure, the facade is glass curtain wall and the lower part is strip foundation. The foundation adopts full row lime soil compaction piles which are 6m length (The relative elevation of the pile bottom is -9.7m). The tunnel mainly passes
through paleosol and old loess. Saturated soft loess is above the vault, the groundwater depth is about 12 ~ 14m (figure 2).

3. Scheme

3.1 Overview

Due to the tunnel directly through the Golden Flower Hotel, the settlement is difficult to control and requirements are high. Furthermore, on the occasions that the soil of building surrounding has been repeatedly destabilized by construction, the geological condition is poor in the scale of excavation and draining outside the pit is not possessed, the tunnel adopts bench drilling and blasting method and divides it into two lines to construct[6-7]. The advanced support is made by using the 108mm long pipe shed, the 42mm advanced small pipe grouting[8] and full-face WSS grouting technology[9-10]. Detailed monitoring program should be constituted to ensure the safety of buildings. The three scheme can be considered to be implemented. Scheme one is that drainage outside the pilot. The scheme two is grouting WSS 1m outside the tunnel and using long pipe shed and drainage. The scheme two is grouting WSS 2m outside the tunnel and using long pipe shed and drainage.

3.2 WSS grouting reinforce

WSS grouting reinforce means double pipe non-shrink double liquid. Firstly, double pipe drill is drilled to the design depth, then grouting is carried out with the synchronous double liquid grouting machine. WSS double liquid grouting is used in the field for pre-reinforcement. According to the construction process, the right line completes grouting one-time. The left line is divided into four times to implement grouting, and liquid is injected every 10m one time. Grouting is carried out with excavating at same time. In the excavation process, the 2m grout wall is reserved and the grouting plan is shown in figure 3. When cyclic grouting is completed, testing grouting effect by borehole sampling method. If it meets the requirements of excavation, the next construction job will be started.

![Figure 3. left line tunnel WSS grouting plan.](image)

3.3 Construction of long pipe shed

The long line pipe shed and single row grouting small pipe are used as the advanced support in the left line of tunnel. The two pilot tunnels located at right upper and right middle of left line shield translation well of Changtong interval are used as platforms. The 39m long pipe shed of the left line tunnel is completed by one-time which is from south to north.

4. Numerical analysis
4.1 Model establishment
To ensure the safety of construction and choose the most effective and reliable reinforcement measures, PLAXIS 2D is used to study the subsidence caused by tunneling underneath buildings before the scheme is determined. The soil is divided into 5 layers, each layer of soil depth: 1.2m, 7.6m, 1.0m, 4.2m, 9.5m. The tunnel deeps 10m, section size is 6.40 m x 6.80m (width x height). The size of the Golden Flower Hotel is 32m x 32m (width x height). The stratigraphic structure parameters are selected according to the geological prospecting data and tunnel support parameters use experiential values (table 1).

Table 1. Physical and mechanical parameters of soil layers and tunnel support.

| Name            | Volumetric weight/(KN/m³) | Elastic Modulus/(MPa) | Poisson ratio | Cohesive forces/(KPa) | The angle of internal friction/(°) | Lateral pressure coefficient |
|-----------------|---------------------------|-----------------------|---------------|-----------------------|-----------------------------------|-------------------------------|
| Plain fill      | 16.5                      | 6.0                   | 0.37          | 10                    | 10                                | 0.7                           |
| New loess       | 19.3                      | 6.5                   | 0.33          | 27                    | 17                                | 0.5                           |
| Saturated Soft loess | 19.8                      | 5.5                   | 0.33          | 30                    | 17.5                              | 0.5                           |
| Paleosol        | 19.5                      | 7.0                   | 0.33          | 31                    | 17.5                              | 0.5                           |
| Old loess       | 20.2                      | 8.0                   | 0.33          | 36                    | 18.3                              | 0.5                           |
| Shotcrete       | 25.0                      | 2.5×10⁴               | 0.2           |                       |                                   |                               |
| Anchor bolt     | 78.5                      | 2.1×10⁵               | 0.3           |                       |                                   |                               |
| Pipe shed       | 21.5                      | 1.2×10⁵               | 0.2           |                       |                                   |                               |
| Grouting        | 21.0                      | 12.0                  | 0.3           |                       |                                   |                               |

The structure deformation of Golden Flower Hotel is very small because of its long distance from the tunnel, the structure can be simplified into 4 span frames. The strip foundation is simulated by plate element. The beam element is used in lime soil compaction pile and pipe shed, and the others are simulated by two-dimensional element[11-12].

4.2 Results analysis
As is shown in figure 4 and figure 5 respectively, it can be seen that the reasonable reinforcement measures can significantly reduce the deformation of soil and effectively control the settlement of the building. In working condition 1, the maximum vertical displacement reaches 63.83mm after excavation, and the differential settlement is about 40mm. In working condition 2, the maximum vertical displacement of the Golden Flower Hotel is 31.10mm, and the differential settlement is about 28mm. In the condition 3, the maximum settlement of the Golden Flower Hotel is 19.22mm and the differential settlement is about 17mm. In contrast, in case 3, the overall settlement and differential settlement of the building can be significantly reduced. According to 《code for design of building foundation》（GB50007-2011）, the overall tilt is 17/32000<0.004 which meets the requirements. In working condition 3, the subsidence value of initial support and the Golden Flower Hotel is very small, which is only 0.5mm. The result shows that the consolidation of 2m deep WSS grouting basically eliminates the formation of water loss consolidation settlement, the construction scheme of strengthening 2m is more reasonable.
5. Monitoring results
The settlement curves of several key points are shown in figure 6, the following conclusions can be obtained: 1.Before the tunnel excavation, the cumulative settlement of the ground surface has reached 4 ~ 8cm, which is caused by the surrounding construction and this condition increases the difficulty of settlement control. 2. There are several obvious upward trends of 2 ~ 3mm in the curve, and it is coincided with the time of WSS cyclic grouting in the cave, which shows that it has certain mitigation and inhibition effect on the ground subsidence. 3. Initial support has finished on August 24th, then the settlement is obviously slowed down, all in the range of 1 ~ 2mm, which indicates that after finishing the initial support of the tunnel. The subsequent construction has little effect on the settlement, which accounts for about 15%.

The left line has been excavated since July 1, 2015, it took 92 days to complete the second lining construction and the tunnel successfully underneath the structure on September 30, 2015. In the process of construction, the glass curtain wall building of Golden Flower Hotel is always in a safe and controlled state, the effectiveness of the reinforcement measures and the results of numerical simulation are also verified.

6. Conclusion
1. The whole process of the shallow tunnel underneath glass curtain wall building is analyzed, which can effectively evaluate the impact on buildings, prejudge key elements that affecting safety of the building and theoretical reference can be provided for similar projects.

2. To set up long pipe shed at once, start WSS grouting in tunnel and combine with settlement monitoring can control settlement deformation of the structure or earth surface. Compared with the unreinforced measures, foundation settlement has reduced by 69.89% and uneven settlement has reduced by 57.5%.
3. Using the monitoring data to feedback the effect of each construction process. Adjusting the construction parameters in time during the process of function, and ensuring that the settlement deformation is under the control standard.

4. WSS grouting can strengthen the formation and reduce the water loss of stratum and consolidation settlement under the condition of non-precipitation.

5. Under the reasonable and effective grouting reinforcement measures, it is feasible to excavate the loess tunnel underneath the glass curtain wall buildings.

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