Design and Construction Optimization of Shield Cutterhead Inspection Shaft Based on Numerical Analysis

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Abstract. As an effective way to inspect and maintain the shield cutterhead, the safety of the inspection shaft is very important in the process of shield tunneling into the shaft. In this study, numerical analysis was adopted to study the interaction of shaft excavation and shield tunneling process and the response law of stratum deformation. Research shows that during the process of the shield tunnelling into the shaft, the bending moment of the enhanced segment of the shaft has the largest change, followed by the lower part of the regular segment and the shield segment. The smaller the shaft excavation space and the more timely the support, the smaller the ground settlement and influence range. The closer the shield support stress ratio is to 1, the smaller the disturbed area of the stratum. It is suggested that the structure strength, monitoring points and monitoring frequency of the enhanced segment and the lower part of the regular segment need to be strengthened. The construction schedule and safety should be taken into consideration when determining the shaft excavation space and shield support pressure.

1. Introduction
With the improvement of the mechanization level of metro construction, the shield construction of tunnels has become the most commonly used construction method [1]. Affected by the highly abrasive geological conditions and the service life of shield cutterhead, the maintenance work in shield construction is indispensable [2-5]. The shield cutter tools are easily worn in sandy cobble strataums. When tunneling in such strataums, the cutterhead needs to be repaired almost every 200 to 300 meters [6]. The construction of inspection shaft can provide spacious operation space for the cutterhead inspection and repair, the cutterhead repair is fast, safe and reliable [7-8]. Li and Yuan [9] introduced the technology of bolting and shotcreting and re-driving hollow pile for cutterhead repair based on the background of Beijing Diameter Line shield inspection shaft. However, the research on the interaction between shaft excavation and shield tunneling is insufficient.

In this paper, the finite element software is adopted to analyse the whole process of shaft excavation and shield tunneling, to study the structural response of shaft lining, and to discuss the law of ground deformation induced by construction and design factors. This study could provide guidance for the design and construction of the shield inspection shaft.

2. Engineering background

2.1. Project overview
The shield inspection shaft is located in Fengtai District, Beijing, China. The plane shape of the shaft is a waisted circle, in which the radius of two semicircles is 1.5 m, the length of the middle straight section is 0.6 m. The depth of the shaft is 24.1 m. The shaft is located on the axis of the right shield tunnel. The stratum that the shaft traversed in turn are: miscellaneous fill, clayey silt, silty clay, fine sand and sandy gravel.

The project is a double track tunnel with a center distance of 15 m. The two tunnels have the same size. The outer diameter of cutterhead is 9.04 m, the outer diameter of tunnel lining is 8.8 m, the thickness of lining is 0.45 m, and the ring width of segment is 1.6 m.

2.2. Shaft support and construction scheme
The prefabricated corrugated steel plate with pitch of 150 mm, depth of 50 mm and base thickness of 5 mm is used as the lining structure of the shaft. The grouting is filled between the corrugated steel plate and the soil. The I-steel support is set in the middle of the waisted circle. After the shaft is excavated, the soil on the side wall of the shaft has a short stress release process, and then the corrugated steel plate assembly and back grouting construction are carried out in time.

3. Three-dimensional finite element analysis of the whole construction process

3.1. Numerical model
The length, width and height of the model are 100 m, 80 m and 55 m respectively. Apply vertical and horizontal constraints at the bottom of the model, and apply horizontal constraints around the model. The numerical model is shown in Figure 1.

During the construction of the shaft, the surrounding soil at the location of the shield maintenance is reinforced to ensure the safety of the shield tunneling process. Figure 2 shows the positional relationship between shaft, reinforcement zone and tunnel. The scope of the reinforcement zone is 3 m above the top of the shield and 3 m below the bottom of the shield. The left and right sides of the shield are 3 m outwards.

In this paper, GTS NX is applied to establish the geometric model and generate the mesh, and then the mesh information is imported into FLAC3D to simulate the construction of shaft and tunnel.

3.2. Model parameters

3.2.1. Stratum parameters. Based on the stratum of the project site, the stratum parameters are obtained by generalizing the stratum. As shown in Table 1, the upper part of the generalized stratum is silt, and the lower part is sandy gravel. The Mohr-Coulomb model is applied.
| Stratum  | Depth (m) | Compression modulus (MPa) | Poisson’s ratio | Density (kg/m³) | Cohesion (kPa) | Friction angle (°) |
|----------|-----------|---------------------------|----------------|-----------------|----------------|-------------------|
| Silt     | 0-13.5    | 8                         | 0.3            | 1900            | 17             | 28                |
| Sandy gravel | 13.5-55 | 45                        | 0.25           | 2050            | 0.5            | 40                |

### 3.2.2. Shaft and shield construction parameters.

The thickness and elastic modulus of the shaft lining are calculated according to the principle of equivalent stiffness. The equivalent parameters of the shaft lining and the support parameters of shield are shown in Table 2.

| Structure type       | Constitutive model | Elastic modulus (MPa) | Poisson’s ratio | Density (kg/m³) | Thickness (m) |
|----------------------|--------------------|-----------------------|-----------------|-----------------|---------------|
| Shaft support structure | Liner element      | 21500                 | 0.3             | 7850            | 0.06          |
| Reinforcement body  | Elastic model       | 200                   | 0.2             | 2150            | -             |
| Shield shell         | Shell element       | 210000                | 0.3             | 7850            | 0.3           |
| Tunnel lining        | Shell element       | 27600                 | 0.17            | 2500            | 0.45          |

### 3.3. Simulation of shaft excavation and shield tunneling

The construction sequence of shaft excavation and shield cutterhead maintenance is as follows:

- The shaft was excavated and supported to a depth of 18 m, as shown in Figure 3a.
- Grouting was carried out in the reinforcement zone, and the shaft continued to be excavated and supported to a depth of 28 m, as shown in Figure 3b.
- Backfill the shaft to a depth of 15.5 m, as shown in Figure 3c.
- The shield tunneled into the shaft, and the backfilled soil in the shaft was excavated, as shown in Figure 3d.

![Figure 3](image-url)  
**Figure 3.** The construction sequence of shaft excavation and shield tunneling.

### 3.4. Response of shaft support structure affected by shield tunneling

The internal force of shaft support structure in the process of shield tunneling into shaft is obtained by simulation. When the distance between the shield cutterhead and the shaft wall is from far to near (from 13.1 m to -1.3 m), the bending moment change of the shaft structure is shown in Figure 4.

It can be seen from Figure 4 that as the distance between the shield cutterhead and the shaft wall gradually decreasing, the bending moment of the shaft support structure is gradually increasing. The bending moment in the lower part of the regular segment increases obviously. The bending moment of the enhanced segment changes greatly, and the bending direction of the straight section and the semicircle section changes. The bending moment of the shield segment is relatively less affected.

Figure 5 shows the variation curve of the maximum bending moment of the shaft support structure with the distance between the shield cutterhead and the shaft wall. It can be seen from Figure 5 that...
when the distance between the shield cutterhead and the shaft wall is less than 9 m (approximately equal to the diameter of the cutterhead), the bending moment of shaft structure increases rapidly. The maximum bending moment of the shaft structure is 35.5 kN·m, and the maximum bending moment is increased by about 47%. It can also be seen from Figure 4 that the maximum bending moment occurs at the enhanced segment.

![Figure 4. Cloud diagram of bending moment of the shaft support structure during the shield tunneling into the shaft.](image)

![Figure 5. Variation curve of the maximum bending moment of the shaft support structure with the distance between the shield cutterhead and the shaft wall.](image)

The analysis shows that the increase of the supporting structure bending moment caused by the shield tunneling needs to be considered in the design of the shaft structure, and the strength of the supporting structure within the enhanced segment needs to be strengthened. It is recommended to strengthen the structural monitoring of the enhanced segment and the lower part of the regular segment in the process of shield tunneling, so as to grasp the shaft safety situation in real time.

4. Design and Construction Optimization analysis

4.1. Influencing factors of ground settlement induced by shaft construction
4.1.1. Excavation space. The excavation spaces of 0.5 m, 1 m and 1.5 m were taken respectively for analysis. When the shaft is excavated to a depth of 20 m, the ground settlement at different distances from the shaft wall are shown in Figure 6.

It can be seen from Figure 6 that the settlement at the shaft wall is the largest, and the settlement gradually decreases with the increase of the distance from the shaft wall. The smaller the excavation space, the smaller the ground settlement and influence area.

4.1.2. Supporting time. The stress release rates of 0.2, 0.5 and 0.8 were taken respectively to analyse the influence of the closing speed of supporting structure on the ground settlement. The greater the stress release rate is, the less timely the support is after excavation. Figure 7 shows the ground settlement under different stress release rates.

It can be seen from Figure 7 that the greater the stress release rate, the greater the ground settlement and influence area. The prefabricated corrugated steel plate used in this project can be supported immediately after the excavation is completed, thereby minimizing the stress release of the stratum and reducing the ground settlement.

4.2. Stratum disturbance under the influence of shield support pressure
The support stress ratio ($\lambda$) is adopted to express the size of support pressure. The support stress ratio is the ratio of the support pressure at the center of the shield cutterhead to the static earth pressure of the original stratum at the center of the tunnel. The support stress ratio of 0.1, 0.5, 1.1 and 1.3 were taken respectively to analyse the stratum disturbance.

4.2.1. Ground settlement in front of the excavation face. Figure 8 shows the ground settlement at 10 m in front of the shield excavation face under the condition that the support stress ratio is equal to 0.1, 0.5 and 1.1 respectively. It can be seen that the smaller the support stress ratio is, the wider the settlement trough is, and the greater the settlement value is.
4.2.2. Stress variation in the stratum. Figure 9 shows the stress distribution along the tunnel axis under different support stress ratios. It can be seen that when the $\lambda$ is less than 1, the stress in the stress-affected area in front of the excavation face increases gradually. When the $\lambda$ is greater than 1, the stress in front of the excavation face first increases and then decreases. When the $\lambda$ is equal to 1.3, the maximum stress is 0.3 times higher than the initial stress.

In summary, the greater $|\lambda-1|$ is, the more disturbed the soil is. Excessive support pressure will increase the additional stress of soil, which is not conducive to the safety of shaft structure. Therefore, it is recommended to adopt decompression tunneling during the shield tunneling into the shaft. It is necessary to combine the relationship between the support stress ratio and the stress affected area to reasonably select the support pressure and the timing of decompression.

5. Conclusion
During the process of the shield tunnelling into the shaft, the bending moment of the enhanced segment of the shaft has the largest change, followed by the lower part of the regular segment and the shield segment. The structure strength, monitoring points and monitoring frequency of the enhanced segment and the lower part of the regular segment need to be increased.

The smaller the shaft excavation space and the more timely the support, the smaller the ground settlement and influence range. It is suggested that the excavation space should be reduced and the excavation face of shaft should be closed as soon as possible.

The stratum disturbance is greatly affected by the shield support pressure. It is recommended to adopt decompression tunneling during the shield tunneling into the shaft, and to reasonably select the support pressure and the timing of decompression.

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