Risk Factor Recognition of Shield Tunnel Crossing Underneath the Existing Subway Tunnel

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Abstract. Studying and controlling the risk factors of shield tunnel crossing underneath the adjacent existing subway tunnel will be of great significance for guaranteeing the safety of tunnel structure. Under the background of subway undercrossing engineering in Shenzhen, 3D finite element models under different working conditions were established using the theory of orthogonal experimental design. The disturbing impacts generated by newly built tunnel shield crossing beneath the existing tunnel were explored in consideration of different factors. Based on the impact degrees of different experimental indexes, the priority and weight of each index were determined via the analyses of range and variance in the orthogonal experiment. The results show that the clear distance and spatial angle between new and old tunnels, and soil chamber pressure exert highly significant impacts on the settlement of the existing tunnel structure; the maximum tensile stress of the existing tunnel structure is significantly impacted by the clear distance, spacing, thickness of overburden layer, and angle; the settlement value of the existing tunnel is extremely sensitive to the soil chamber pressure, with the impact weight reaching 24.9%, and the maximum tensile stress of the existing tunnel is sensitive to the change in the thickness of overburden layer: With the increase in the thickness of overburden layer, the maximum tensile stress presents a significant trend of progressive increase, and the impact weight reaches 19.25%. The study results will be of reference significance to the safety construction of shield tunnel crossing beneath the adjacent existing subway tunnel.

1. Introduction

With the vigorous development of urban rail transit in China, the operating mileage of urban subway tunnels is increasing year by year, urban rail transit networks are continuously densified, and the buildings (structures) and subway lines cross each other in urban underground spaces, thus forming a complicated “subway domain”, which, on the one hand, effectively solves the traffic problems in daily life and work and relieve traffic jam, and on the other hand, brings about numerous difficulties to the subsequent underground tunnel engineering construction [1]. In order to ensure the smooth implementation of transportation and land planning, and maximize the use efficiency of urban underground spaces, newly built tunnels will unavoidably run across the existing underground buildings (structures) like tunnels, and this trend will be continuously upgraded with the underground space development and utilization. In urban areas, the construction of newly built subway tunnels crossing the
existing subway lines in operation is a typical situation of adjacent construction. Belonging to a large-scale transportation system, a subway tunnel usually consists of double-truck tunnels, evidently indicating its high importance degree and great strictness in its deformation control.

Predecessors have carried out much research work regarding the impacts of shield tunnel crossing underneath the adjacent existing tunnels on the deformation and internal force of the existing tunnels. For instance, Fang Y et al. [2] used the 3D finite element method to simulate the parallel shield tunneling construction, and in full consideration of the interaction between shield tunneling machine and segmental lining, and transverse isotropy of segmental lining structure, they studied the change laws of displacement, deformation, and internal force of the existing tunnel during the dynamic driving of newly built tunnel; through a study based on FLAC 3D finite difference method, Bai H W [3] found that grouting reinforcement of the strata around the existing tunnel could control the settlement deformation of the existing tunnel better than the reinforcement of the existing tunnel lining structure itself; Shen X W et al. [4] established a 3D finite element model for the driving process of shield tunnel from beneath the pipeline via MIDAS/GTS software, followed by a finite element analysis of impacts of parameters (such as distance from shield driving face, relative burial depth of pipeline and tunnel, and relative stiffness of pipe and clay) on the stress-carrying results of the pipeline; Ding D Y et al. [5] used the 3D finite element method to simulate the construction process of large-diameter earth pressure balance shield (outer diameter: 10 m) crossing the underground excavated air duct in the subway station, analyzed the impacts of the large-diameter shield tunnel undercrossing on the deformation and stress of the air duct, and proposed the safety measures for shield construction; Hu J et al. [6] conducted 3D finite element numerical simulation analysis of mechanical behaviors in the construction process of a shield tunnel crossing underneath the existing underground subway tunnel, and figured out the impact laws of positional relationships of different shield driving spaces on the tunnel deformation mode; Fang M et al. [7] used the 3D finite element method to study the impact of the orthogonal undercrossing construction of a newly built tunnel shield on the displacement of the existing tunnel; under the practical background of undercrossing engineering, Li P et al. [8] performed the 3D numerical simulation, and indicated that the safety of the existing tunnel structure could be ensured by strictly controlling the shield driving or taking pertinent measures. Besides the impacts of undercrossing construction on the existing tunnel structure, some scholars have also considered the impacts of single or multiple factors. For example, based on a concrete project, Li Q et al. [9] and Li T P et al. [10] analytically investigated the impact degrees of pressure change of muddy water or thrust of tunnel face on the existing tunnel; Lin Z J [11] explored the construction parameters like soil chamber pressure and grouting pressure as well as stratal reinforcement measures; Hu W et al. [12] investigated the impact laws of factors like geological conditions, spacing, jacking force, and burial depth of surrounding rocks on the strata and existing tunnel structure via the numerical simulation calculation method, and this study is of great significance.

Based on the predecessors’ studies, the actual working conditions were combined to further explore the deformation of the existing tunnel structure and the change in its internal force in full consideration of various factors (construction method of existing tunnel, clear distance between new and old tunnels, two-line spacing of newly built tunnel, thickness of overburden layer in the existing tunnel, the texture at the soil layer the existing tunnel is located, grouting filling rate, and soil chamber pressure), expecting to provide the construction reference for more shield crossing projects closely beneath the existing tunnels.

2. Modeling and scheme design

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2.1. Calculation model

The dimensions of the calculation model were length × width × height= 80 m × 60 m × 50 m. The excavation by steps, which coincided with the practical situation more, was adopted by this model to simulate the shield driving process, and the “one-ring one-step” excavation was used to simulate the
whole tunneling process. The unloading process in shield excavation was simulated using the displacement release method. The equivalent circular zone had different elasticity moduli in different construction steps by changing its material parameters, in order to simulate the synchronous grouting slurry hardening process. The numerical model is shown in Figure 1.

![Numerical Simulation Model](image)

(a) Overall Model  (b) Spatial Relationship

Figure 1 Numerical Simulation Model

2.2. Impact factors

The shield adjacent crossing construction is impacted by many factors, which, according to their different properties, can be mainly divided into spatial parameters, material parameters, construction parameters, and other parameters. So-called spatial parameters refer to parameters determining the spatial positional relationship between two tunnels in the adjacent crossing construction, mainly including spatial angle ($\theta$) and tunnel spacing (d), etc. The impact of spatial parameters on the adjacent crossing construction is mainly manifested by the horizontal curve and longitudinal curve planning of the tunnels. In principle, the adjacent crossing construction should be avoided as much as possible, and when this becomes unavoidable, the advantageous line planning should be conducted.

The material parameters include parameters of built tunnel, soil mass parameters, and parameters of shield and tunnel under construction, all of which are mainly applied to design and calculation, but they also have a great bearing on the construction. The parameters of built tunnel include tunnel dimensions, tunnel material parameters, etc., among which the parameters related to longitudinal stiffness and transverse stiffness and those related to volume weight have been extensively used in the adjacent crossing construction. The longitudinal stiffness and transverse stiffness of tunnel are mainly used to evaluate the longitudinal and circumferential deformation of built tunnel under the disturbance of adjacent crossing construction, while the volume weight parameter is mainly adopted to evaluate the impact of built tunnel on the soil pressure beneath and the upward floating of built tunnel during the crossing construction. The soil mass serves as both the main load factor and disturbance transfer medium in the adjacent crossing construction. The parameters used to estimate the load include soil unit weight at each layer, lateral pressure coefficient, thickness of soil layer, groundwater level, etc. The soil mass parameters used to transfer the disturbance include elasticity modulus, Poisson’s ratio, and related plastic parameters, etc. The parameters of shield and tunnel under construction include dimensions and weights of shield and tunnel, etc., which are mainly used to estimate the scope of disturbance, unloading in the crossing construction and so on.

In full consideration of impacts of spatial parameters, material parameters, and construction parameters on the undercrossing construction, the construction method of the existing tunnel, clear distance between new and old tunnels, two-line spacing of newly built tunnel, thickness of overburden layer in the existing tunnel, texture of soil layer where the existing tunnel is located, grouting filling rate, and soil chamber pressure were selected in this experiment.

2.3. Numerical scheme design

Two indexes were selected for the experimental analysis, that is, maximum settlement of the existing tunnel ($y_1$) and maximum tensile stress borne by the existing tunnel ($y_2$). Eight impact factors were chosen, where two levels were selected for the construction method of the existing tunnel while three levels were selected for each of the other factors, and the orthogonal experimental design was
implemented using the one-factor two-level and seven-factor three-level mixed orthogonal table $L_{18} (2^1\times 3^7)$. The serial numbers of impact factors and their levels are seen in Table 1.

### Table 1 Impact factors and their levels

| Level | Factor                        | Level | Construction method (A) | Clear distance (B)/m | Spacing (C)/m | Thickness of overburden layer (D)/m | Angle (E)/° | Soil texture (F) | Grouting filling rate (G)% | Soil chamber pressure (H) |
|-------|-------------------------------|-------|-------------------------|----------------------|--------------|----------------------------------|-------------|------------------|----------------------------|--------------------------|
| 1     | Shield                        | 1     | Shield                 | 1.0                  | 8            | 6                                | 30          | I                | 100                        | Pressure maintaining     |
| 2     | Mine                          | 2     | Mine                   | 2.5                  | 16           | 12                               | 60          | II               | 80                         | Under-pressure           |
| 3     | —                             | 3     | —                      | 4.0                  | 12           | 18                               | 90          | III              | 40                         | Pseudo-pressure          |

Note: Three types of soil texture correspond to I clay, II sandy soil, and III completely weathered rock formation, respectively.

### 3. Analysis of range for numerical results

Numerical models were constructed for 18 different working conditions to solve the maximum settlement and maximum tensile stress corresponding to the existing tunnel, and the statistical calculation results are listed in Table 2.

### Table 2 Numerical simulation results

| Simulation No. | A | B | C | D | E | F | G | H | Maximum settlement $y_1$ | Maximum tensile stress $y_2$ |
|----------------|---|---|---|---|---|---|---|---|----------------------------|----------------------------|
| 1              | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8.96                       | 2.149                      |
| 2              | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 9.04                       | 1.456                      |
| 3              | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 10.9                       | 2.98                       |
| 4              | 1 | 2 | 1 | 2 | 2 | 3 | 3 | 1 | 15.5                       | 2.398                      |
| 5              | 1 | 2 | 2 | 2 | 3 | 3 | 1 | 1 | 7.56                       | 1.932                      |
| 6              | 1 | 2 | 3 | 3 | 1 | 1 | 2 | 2 | 8.48                       | 1.696                      |
| 7              | 1 | 3 | 1 | 2 | 1 | 3 | 2 | 3 | 9.1                        | 2.29                       |
| 8              | 1 | 3 | 2 | 3 | 2 | 2 | 1 | 1 | 7.21                       | 1.603                      |
| 9              | 1 | 3 | 3 | 1 | 3 | 2 | 1 | 2 | 5.52                       | 1.024                      |
| 10             | 2 | 1 | 1 | 3 | 3 | 2 | 2 | 1 | 6.02                       | 3.15                       |
| 11             | 2 | 1 | 2 | 1 | 1 | 3 | 3 | 2 | 8.48                       | 2.368                      |
| 12             | 2 | 1 | 3 | 2 | 2 | 1 | 1 | 3 | 13.6                       | 1.42                       |
| 13             | 2 | 2 | 1 | 2 | 1 | 3 | 2 | 3 | 7.76                       | 2.216                      |
| 14             | 2 | 2 | 2 | 3 | 1 | 2 | 1 | 3 | 10.1                       | 2.93                       |
| 15             | 2 | 2 | 3 | 1 | 2 | 3 | 2 | 1 | 8.33                       | 0.924                      |
| 16             | 2 | 3 | 1 | 3 | 2 | 3 | 1 | 2 | 10.96                      | 2.12                       |
| 17             | 2 | 3 | 2 | 1 | 3 | 1 | 2 | 3 | 5.9                        | 1.12                       |
| 18             | 2 | 3 | 3 | 2 | 1 | 2 | 3 | 1 | 5.74                       | 1.813                      |

From the analysis of range, the impact degrees of the factors on the settlement value were sorted as soil chamber pressure (H), angle (E), clear distance (B), spacing (C), grouting filling rate (G), construction method (A), soil texture (F), and thickness of overburden layer (D) in a descending order, and those on the maximum tensile stress were sorted as thickness of overburden layer (D), spacing (C), clear distance (B), angle (E), soil texture (F), grouting filling rate (G), soil chamber pressure (H), and construction method (A) in a descending order.

The weights of impact factors obtained according to the proportion occupied by the range of each factor under different indexes are seen in Table 3.
Table.3 Factor weights

| Index | Construction method (A) | Clear distance (B) | Spacing (C) | Thickness of overburden layer (D) | Angle (E) | Soil texture (F) | Grouting filling rate (G) | Soil chamber pressure (H) |
|-------|-------------------------|--------------------|-------------|----------------------------------|-----------|----------------|--------------------------|-------------------------|
| \( y_1 \) | 6.64 | 15.56 | 11.71 | 1.15 | 24.55 | 4.00 | 11.50 | 24.90 |
| \( y_2 \) | 2.72 | 15.45 | 17.44 | 19.25 | 15.33 | 9.96 | 10.69 | 9.16 |

4. Factor impact laws
The orthogonal analysis of maximum settlement and maximum tensile stress of the existing tunnel was implemented under 18 different working conditions, and then the impact laws of different factors on the maximum settlement and maximum tensile stress of the existing tunnel are shown in Fig. 2-5.

Figure 2 Impact laws of construction method (A), clear distance (B), spacing (C), and thickness of overburden layer (D) on the maximum settlement of the existing tunnel

As shown in Figure 2 and Figure 3, the soil chamber pressure (HP), which was transited from pressure maintaining state into pseudo-pressure state, had the maximum impact degree on the settlement of the existing tunnel, and the settlement value presented progressive increase, with the increase amplitude reaching 48.6%; the angle (E) had the second largest impact on the settlement value: As the angle was increased from 30° to 90°, the angle 60° appeared to reach the maximum impact degree on the settlement; the clear distance (B) between new and old tunnels followed: When the clear distance was changed from 2.5 m into 4 m, the settlement value was significantly reduced, and the decrease amplitude was 23%.

Figure 3 Impact law of angle (E), soil texture (F), grouting filling rate (G), and soil chamber pressure (H) on the maximum settlement of the existing tunnel

From Figure 3 and Figure 4, the thickness of overburden layer (D) had the maximum impact on the tensile stress of the existing tunnel: The maximum tensile stress was significantly increased (increase amplitude: 4.6%) as the thickness of overburden layer was changed from 6 m to 18 m; followed by
spacing (C): When the two-line spacing of newly built tunnel was within 8 m-16 m, the maximum tensile stress reached the minimum value at 12 m; the clear distance (B) between new and old tunnels followed: As the clear distance was changed from 1 m to 4 m, the maximum tensile stress presented a significant decreasing trend, with the decrease amplitude of 27.1%.

Figure 3 Impact laws of construction method (A), clear distance (B), spacing (C), and thickness of overburden layer (D) on the maximum tensile stress of the existing tunnel

Figure 4 Impact laws of angle (E), soil texture (F), grouting filling rate (G), and soil chamber pressure (H) on the maximum tensile stress of the existing tunnel

5. Analysis of variance for numerical
Two methods have been commonly used to analyze the orthogonal experimental results: The one method is intuitive analysis method, namely analysis of range; the other one is analysis of variance. The former is simple and intuitive with small calculated quantity, but it fails to estimate the errors or accurately estimate the impact degree of each factor on the experimental result, and it is especially inapplicable to the experiment with over three levels and needing the consideration of interaction. Hence, the analysis of range may be used to compensate for these deficiencies of the intuitive analysis method. Based on the orthogonal experimental results, the mean value of each index, and the square sum of factor deviations were solved, and significance level of each factor was solved via F test. The analysis results of variance are listed in Table 4 and Table 5, where R is range, S is square sum of factor deviations (inter-group deviation), F is ratio of factors (ratio of inter-group mean square to intra-group mean square), "*" means significant, "***" represents highly significant, and "O" denotes a certain impact.

According to the analysis results of variance, the clear distance between new and old tunnels, spatial angle, and soil chamber pressure had highly significant impacts on the settlement of the existing tunnel, while the two-line spacing of newly built tunnel, and grouting filling rate had significant impacts on the settlement; the maximum tensile stress of the existing tunnel was highly significantly impacted by the
clear distance, spacing, thickness of overburden layer, and angle, and significantly impacted by the soil texture, grouting filling rate, and soil chamber pressure.

| Table. 4 Analysis Results of Variance in Orthogonal Experiment (Maximum Settlement) |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Item             | Factor |       |       |       |       |       |       |       |
|                  | A      | B      | C      | D      | E      | F      | G      | H      |
| **R_j**          | 5.38   | 13.30  | 10.01  | 0.98   | 20.98  | 3.42   | 9.83   | 21.28  |
| **S**            | 1.61   | 18.63  | 8.41   | 0.10   | 37.88  | 1.30   | 9.66   | 39.72  |
| **F**            | 1.77   | 10.24  | 4.62   | 0.05   | 20.82  | 0.71   | 5.31   | 21.83  |
| Significance     | **    | *      | **    | *      | **    | **    | **    | **    |

| Table. 5 Analysis Results of Variance in Orthogonal Experiment (Maximum Tensile Stress) |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Item             | Factor |       |       |       |       |       |       |       |
|                  | A      | B      | C      | D      | E      | F      | G      | H      |
| **R_j**          | 0.61   | 3.67   | 4.15   | 4.58   | 3.65   | 2.37   | 2.54   | 2.18   |
| **S**            | 0.02   | 1.13   | 1.46   | 1.84   | 1.22   | 0.60   | 0.56   | 0.40   |
| **F**            | 4.24   | 114.54 | 148.38 | 187.07 | 123.56 | 61.16  | 56.93  | 40.97  |
| Significance     | **    | **    | **    | **    | *      | *      | *      | *      |

6. Conclusions

The theory of orthogonal experimental design was used to establish 3D finite element models under different working conditions, and explore the disturbing impacts of newly built tunnel shield undercrossing on the existing tunnel under the actions of different factors. The conclusions were drawn as follows:

1. According to the analysis of range, the impact degrees of different factors on the settlement of the existing tunnel are sorted as soil chamber pressure, angle, clear distance, spacing, grouting filling rate, construction method, soil texture, and thickness of overburden layer in a descending order, and those on the maximum tensile stress of the existing tunnel are sorted as thickness of overburden layer, spacing, clear distance, angle, soil texture, grouting filling rate, soil chamber pressure, and construction method in a descending order.

2. From the analysis of variance, the settlement of the existing tunnel is highly significantly impacted by the clear distance between new and old tunnels, spatial angle, and soil chamber pressure, and its maximum tensile stress is highly significantly impacted by the clear distance, spacing, thickness of overburden layer, and angle.

3. The settlement of the existing tunnel is extremely sensitive to the soil chamber pressure, which is transited from pressure maintaining state into pseudo-pressure state, and the increase amplitude of settlement is apparent, reaching 48.6%. followed by the impact degree of angle, and the angle 60° reaches the peak impact degree on the settlement; the maximum tensile stress of the existing tunnel is sensitive to the thickness of overburden layer: With the increase in the thickness of overburden layer, the maximum tensile stress presents a significant progressive increasing trend, and the impact degree reaches 19.25%; the two-line spacing of newly built tunnel follows, accounting for a weight of 17.44%.

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