Seismic analysis of a transition tunnel constructed with TBM and mining method

Song Yang¹, Ruozhou Li² *, Pengyuan Li¹, Chao Wang¹, Fei Yu¹, Yong Yuan² and Haitao Yu²

¹Powerchina Roadbridge Group Co., Ltd., Beijing 100048, China
²College of Civil Engineering, Tongji University, Shanghai 200092, China

Abstract. A transition tunnel is generally built to connect a TBM tunnel and a mining tunnel, given the different cross sections associated with each construction method. The transition tunnel may be sensitive to earthquake damage since the tunnel cross-section and stiffness change along the tunnel axis. Studying the seismic performance of the transition tunnel structure, a subtle 3D finite element model is carried out. Comparing with the calculation results of SHAKE91, a reasonable non-reflective boundary condition is used. The concrete adopts an elastoplastic damage constitutive model, and the surrounding rock mass uses an elastoplastic constitutive model based on the Drucker-Prager yield criterion. The effects of different ground motion magnitudes and different types of seismic waves are calculated and analyzed through dynamic time-history method. The calculation results show that the impact range of the construction method butted composite lining section on the tunnel structure of the mine tunnel and the TBM tunnel is about 10m, and the reinforcement of the inner lining will cause a sudden change in the stress of the outside TBM tunnel structure. Moreover, the compressive stress of the surrounding rock and tunnel structure is small, and the structural damage mainly occurs in the area of the arch shoulder and arch foot.

1. Introduction

Tunnels can be constructed by different methods such as immersion, tunnel boring machine (TBM), mining, cut-and-cover, or a combination. A combination of TBM and mining is widely used to build subway tunnels. Typically, tunnels constructed with different tunneling methods have different cross-sections. A mining tunnel normally has a horse-shoe cross-section, while the TBM has a circular cross-section. Additionally, the support also differs the mining tunnel may be supported by cast concrete, while the TBM tunnel is supported by prefabricated concrete segments. Thus, a transition tunnel is normally necessary to connect the TBM and the mining tunnels.

Earthquake damage reconnaissance of underground structures after major earthquakes has shown that any abrupt change of the tunnel cross-section and/or stiffness is one of the most important factors that contribute to damage in tunnels [1-2]. It has also been found that abrupt changes in stiffness or cross-section cause stress concentrations [3]. This is generally related to the notion that the relative stiffness of the structure to that of the surrounding ground is a key factor for the seismic performance of underground structures. Based on the infinite beam-elastic foundation theory, analytical solutions proposed to study the seismic response of tunnels with uniform cross sections [4-7]. For the tunnel liners with sharp stiffness transition, [8] presents an analytical solution to study the longitudinal bending stiffness. Transition tunnels, given that the cross section and surrounding ground change along the tunnel, will have their seismic response changing along their axis. If the transition is not well designed, stress concentrations and potential damage may occur.
For the important problem of seismic response of the transition tunnel constructed by TBM and mining method on Xiamen Linsan Metro Line, based on the established three-dimensional finite element model and the seismic excitation characteristics of complex sites, different ground motion levels and different seismic waveforms are carried out. Large-scale dynamic response simulation study of the docking structure under different earthquake incidence directions, systematically analyzing the seismic response characteristics of the docking structure, reasonably evaluating the seismic safety of its key parts, verifying the design and construction details of key nodes, and make optimization suggestions for structural design.

2. Prototype of the transition tunnel

2.1. Transition tunnel

The Xiamen Line-3 subway tunnel is located in the northeast of the Xiamen Island and connects the Wuyuanwan and Huizhan Centre stations. The tunnel has a total length of 5,052 m, including two sections excavated with a TBM and one with drill-and-blast, as shown in Figure 1. For the east side of the Wuyuanwan station, a shaft is constructed to connect the TBM and the mining tunnels, which are buried in soft soil layers. For the other side, note that the connection has to be completed under sea. It will be very expensive and risky to build a working shaft in water area. Instead, a transition tunnel is proposed to connect the mining and TBM sections at the west side of the Huizhan Centre Station (Figure 1). The transition tunnel is excavated underground directly and supported with concrete liners. Since the construction of a transition tunnel requires a high stability of surrounding ground, the transition tunnel is normally located in the rock ground, as shown in Figure 2.

![Figure 1. Longitudinal vertical section of the Xiamen Line-3 tunnel.](image1.png)

(a) profile of the strata (dimensions in m), (b) shear wave velocities of the ground layers.

![Figure 2. Longitudinal profile of the transition tunnel.](image2.png)

Figure 2 (a) shows the longitudinal profile of the transitional tunnel and lithology, as well as the shear wave velocities, Vs, of the ground layers (Figure 2(b)). Below the surface, a clay layer appears, about 10 m thick, with a Vs of 210 m/sec. Underneath, there is bedrock, a granodiorite, which appears highly
weathered on its top 5 m, where it has a \( V_s \) of 550 m/sec. Below, where the transition tunnel lies, the granodiorite is moderately weathered and has a shear wave velocity of 1200 m/sec.

The transition tunnel between the TBM and mining tunnels is divided into three regions: (1) D1: the mining tunnel; (2) D2: the TBM tunnel; (3) D3: the connecting tunnel, as shown in Figure 3.

![Figure 3. Transition tunnel.](image3)

2.2. Cross sections
The cross-section of the mining tunnel, region D1 in Figure 3, is shown in Figure 4. It has a horse-shoe cross section, as shown in Figure 4. It has inner dimensions of 9,500 mm of height and 8,100 mm of width. The liner has two layers: one, the primary liner, is shotcrete with a thickness of 300 mm; and two, the secondary liner, is cast concrete with a thickness of 450 mm.

![Figure 4. Cross-section of D1: mining tunnel (dimensions in mm).](image4)

Region D2 of the TBM tunnel, in Figure 3, is shown in Figure 5. It has an inner radius of 6000 mm and an outer radius of 6700 mm. The liner consists of six segments along the circumferential direction: one key segment, F, two adjacent segments, L1 and L2, and three normal segments B1 to B3. Each segment has a thickness of 350 mm and a width of 1500 mm. A staggered assembly is adopted to assemble the rings in the longitudinal direction, which are connected with six groups of high strength bolts. The length and diameter of the steel bolts are 545 mm and 30 mm respectively.
Figure 5. Cross-section of D2: TBM tunnel (dimensions in mm).

Region D3, is excavated by drill-and-blast, has a total length of 20 m and a circular cross section of 7,900 mm diameter, as shown in Figure 6. The support, has three layers: the outer layer, in contact with the rock, is cast in place concrete, with a thickness of 600 mm; the intermediate layer is made of segments identical to those of Region D1; and the inner layer, with a thickness of 250 mm, is made of cast concrete.

Figure 6. Cross-section of D3: Connecting tunnel (dimensions in mm).

3. Numerical Model and Parameters
According to the site conditions where the tunnel structure of the docking section is located and the structural characteristics of the composite lining structure, the surrounding rock and the tunnel lining structure are simulated using the usual C3D8R solid elements. The C3D8R solid element in ABAQUS is an 8-node hexahedral element that uses the reduced integration method, and introduces a small amount of artificial "hourglass stiffness" to limit the expansion of the hourglass mode during the calculation of the reduced integration element, making the entire calculation process more stable. The overall finite element model is shown in Figure 7, the structure of the docking section is shown in Figure 8.
3.1. Material model for concrete structure

Concrete uses an elastoplastic damage constitutive model, that is, a continuous and plastic-based damage concrete model, proposed by Lubliner[9]. The basic calculation parameters of the compound lining tunnel structure are shown in Table 1 and Table 2.

Table 1. Basic physical parameters of lining structure concrete.

| Material                  | $\rho$ (kg/m$^3$) | $E$ (GPa) | $\nu$ | Dilation Angle/° | Eccentricity | $f_{b0}/f_{c0}$ | $K$    | Viscosity Parameter |
|---------------------------|------------------|-----------|------|------------------|--------------|-----------------|-------|---------------------|
| C25 concrete              | 2250             | 21        | 0.2  | 30               | 0.1          | 1.16            | 0.6667 | 0.0005              |
| C50 concrete              | 2500             | 33.5      | 0.2  | 30               | 0.1          | 1.16            | 0.6667 | 0.0005              |
| C25 gravel concrete       | 2200             | 15        | 0.25 | 30               | 0.1          | 1.16            | 0.6667 | 0.0005              |
| Shield tunnel segment     | 2550             | 35.5      | 0.2  | 30               | 0.1          | 1.16            | 0.6667 | 0.0005              |

Table 2. Plastic damage model parameters of lining structure concrete.

| Material                  | Damage Parameter | Inelastic Strain | Damage Parameter | Cracking Strain | Damage Parameter | Inelastic Strain | Damage Parameter | Cracking Strain | Damage Parameter | Inelastic Strain | Damage Parameter | Cracking Strain |
|---------------------------|------------------|------------------|------------------|-----------------|------------------|------------------|------------------|-----------------|------------------|------------------|------------------|-----------------|
| C25 concrete              | 0                | 0                | 0                | 0               | 0                | 0                | 0                | 0               | 0                | 0                | 0                | 0               |
| C25 gravel concrete       | 0                | 0                | 0                | 0               | 0                | 0                | 0                | 0               | 0                | 0                | 0                | 0               |
| Shield tunnel segment     | 0                | 0                | 0                | 0               | 0                | 0                | 0                | 0               | 0                | 0                | 0                | 0               |

Figure 7. Three-dimensional finite element overall model.

Figure 8. Structure model of butt joint of composite lining.
3.2. Material model for soil

Under the action of strong earthquakes, the rock mass will yield failure, especially the loose surrounding rock area around the tunnel will be further expanded, so this paper uses the elastoplastic constitutive model based on Drucker-Prager yield criterion to simulate the stress and strain characteristics of the surrounding rock mass. The material parameters of surrounding rocks at various levels are shown in Table 3.

Table 3. Basic physical and mechanical parameters of surrounding rocks

|          | $\rho$ / kg / m$^3$ | E / GPa | $\nu$ | $\phi$ | c / MPa |
|----------|---------------------|---------|-------|--------|---------|
| rock of grade III | 2400                | 7.69    | 0.29  | 36     | 1.2     |
| rock of grade IV  | 2300                | 4.54    | 0.32  | 32     | 0.6     |
| rock of grade V   | 2210                | 1.71    | 0.46  | 28     | 0.4     |
| rock of grade VI  | 1960                | 0.74    | 0.47  | 27.5   | 0.2     |
| Silt layer       | 1800                | 0.20    | 0.48  | 14.5   | 0.03    |

3.3. Boundary conditions and seismic inputs

Infinite element is introduced as an artificial boundary in the ABAQUS calculation model. Compared with the viscous boundary, the infinite element can correctly simulate the boundary condition of zero displacement at infinity in addition to the fact that the far field absorbs seismic wave energy. In addition, the use of infinite element can greatly reduce the number of units and save computing time.

In order to verify the rationality of the lateral boundary width, the thickness of the bedrock at the bottom, and the reflection of the seismic wave at the boundary; the seismic response of the one-dimensional site model and the three-dimensional target finite element model (150m × 250m × 70m) were analysed using SHAKE91 and ABAQUS, comparative analysis of the rationality of the boundary conditions. Through calculation, the ground motion acceleration time-history response and response spectrum at the model tunnel location are taken as comparison indicators. The acceleration time-history comparison curve and the corresponding response spectrum curve are shown in (a) and (b) in Figure 9–Figure 11, respectively.
Through the above comparison, it can be found that the main frequency band of the acceleration response of the design ground motion of the tunnel track surface, the calculation results of SHAKE91 and ABAQUS are 0–10Hz, and the peak value of the acceleration response is also basically close. Therefore, the size of 150m × 250m × 70m used in the finite element calculation model can meet the calculation requirements.

Figure 9. Design time history and frequency spectrum of ground motion acceleration of the track surface.

Figure 10. One-dimensional site surrounding rock acceleration time history and frequency spectrum.

Figure 11. Time history and frequency spectrum of 3D site surrounding rock acceleration.

4. Results and Discussion

4.1. Influence range of docking section
According to the analysis of the influence range of the docking section, the common mining method and shield method section which are not affected by the construction method butt composite lining section are determined. Figure 12 is the peak stress variation curve of the mining tunnel structure in the longitudinal direction, and the distance in the figure represents the distance of the composite lining
section docked with the construction method. It can be seen that the stress distribution at the junction of
the butt and mining tunnel is quite different from the stress at the conventional mining tunnel on the
right. For the maximum principal stress, when the distance is greater than 8m, the stress area of each
key point is stable; for the distribution of the minimum principal stress, the area is stable when the
distance from the butt joint is greater than 6m. This means that the affected area of the tunnel structure
in the mining section is less than 10m.

![Graph](image1)
(a) maximum principal stress.
(b) minimum principal stress.

**Figure 12.** Distribution of the maximum and minimum principal stress peaks in the mining tunnel.

Figure 13 is the peak stress variation curve of the tunnel structure of the shield section in the longitudinal
direction. In the junction area with or without lining reinforcement, there is obvious stress mutation;
meanwhile, the stress distribution pattern in the lining reinforcement area is basically unchanged. For
the non-lining reinforced area, when the distance from the lining is greater than 7m, the stress
distribution at each key point of the maximum principal stress tends to be stable; for the distribution of
the minimum principal stress, the area is stable when the distance from the lining is greater than 10m.
This means that the affected area of the shield tunnel structure is 10m.

![Graph](image2)
(a) maximum principal stress.
(b) minimum principal stress.

**Figure 13.** Distribution of the maximum and minimum principal stress peaks in the shield tunnel.

### 4.2. Deformation characteristics and stress distribution of cross-section structure

The structural clearance deformation is an important indicator to measure the stability of the structure;
in addition, the tunnel structure mainly exhibits elliptical deformation under the action of ground motion.
Therefore, the D1, D2 and D3 sections (Figure 3) were selected to analyse the structural deformation
characteristics of the mining, shield and docking sections and the stress distribution law along the
circumferential direction of the structure; the schematic diagram of the key points of the lining structure
of the mining section is shown in Figure 14, and the other sections are similar.
Figure 14. Schematic diagram of key points of tunnel structure.

Figure 15. Time-history curve of tunnel section clearance deformation.

As shown in the Figure 15, it is obvious that the overall deformation of the structure is small, and the three sections reach the peak deformation at 10.88s. The peak deformations are 2.2mm, 2.3mm, and 1.7mm, respectively. Select the moment when the structure is deformed the most, and analyse the stress distribution of the lining structure and surrounding rock along the hoop.
Figure 16. Distribution diagram of maximum and minimum principal stress in mining section D1

Figure 17. Distribution diagram of structure damage in mining section D1.

For the mining section, compared with the surrounding rock mass, the maximum principal stress of the primary liner and the second liner is larger, and reaches the maximum value in the arch shoulder. Among them, the dotted line represents the ultimate tensile strength of concrete. In addition, the minimum principal stress distribution curve shows that the compressive stress of surrounding rock and lining structure is small.

Figure 18. Distribution diagram of maximum and minimum principal stress of the shield section D2.
For the shield section, it is obvious that compared with the surrounding rock mass, the maximum principal stress of the segment and liner is larger, and reaches the maximum value in the area of the arch shoulder and arch foot. Similar to the tunnel structure stress in the mining section, the compressive stress of the surrounding rock and the tunnel structure is small.

For the docking section D3, it can be seen that compared with the surrounding rock mass, the main stress of the inner liner and the second liner of the docking section is larger, and the ultimate tensile strength of the concrete is reached at the position of the arch foot. Similar to the D1 and D2 structural sections, the compressive stress of the surrounding rock and each tunnel structure is small.
Moreover, it can be discovered that the structural damage mainly occurs in the arch shoulder and arch foot area.

5. Conclusions
In this paper, the dynamic time history analysis of the seismic response in the transition tunnel is carried out through three-dimensional numerical simulation. Based on the numerical simulation, the main stress response time history of each key section of the docking section under the ground motion, the stress abrupt range of the transition tunnel structure, and the tension and compression damage area of each section are analysed.

The research conclusions are as follows:
1. Under the ground motion, the impact range of the docking composite lining section on the mine tunnel and TBM tunnel structure is about 10m.
2. The reinforcement of the inner lining of the composite lining section will lead to sudden stress. During construction, the reinforcement layer needs to be treated to reduce the magnitude of sudden stress changes.
3. Under the ground motion, the stress at the arch shoulder and arch foot of the tunnel reaches the maximum value, the compressive stress of the surrounding rock and the tunnel structure is small, and the structural damage mainly occurs in the arch shoulder and arch foot area.

6. References
[1] Yu H T, Chen J T, Yuan Y and Zhao X 2016 Seismic damage of mountain tunnels during the Wenchuan Strong Earthquake Mount. Sci 13 1958–1972
[2] Chen J T, Yuan Y and Yu H T 2020 Acceleration response of segmental lining tunnel Geotech. Test. J. ASTM 43 660-682
[3] Yu H T, Yuan Y, Qiao Z Z, Gu Y, Yang Z H and Li X D 2013 Seismic analysis of a long tunnel based on multi-scale method Eng. Struct 49 572–587
[4] Miao Y, Shi Y, Luo H and Gao R X 2018 Closed-form solution considering the tangential effect under harmonic line load for an infinite euler-bernoulli beam on elastic foundation Appl. Math. Model 54 21–33
[5] Miao Y, Yao E L, Ruan B and Zhuang H Y 2018 Seismic response of shield tunnel subjected to spatially varying earthquake ground motions Tunn. Undergr. Space Technol 77 216–226
[6] Miao Y, Yao E L, Ruan B, Zhuang H Y, Chen G X and Long X H 2018 Improved Hilbert spectral representation method and its application to seismic analysis of shield tunnel subjected to spatially correlated ground motions Soil Dyn. Earthq. Eng 111 119–130
[7] Yu H T, Cai C, Bobet A, Zhao X and Yuan Y 2019 Analytical solution for longitudinal bending stiffness of shield tunnels Tunn. Undergr. Space Technol 83 27–34
[8] Yu H T, Zhang Z W, Chen J T, Bobet A, Zhao X and Yuan Y 2018 Analytical solution for longitudinal seismic response of tunnel liners with sharp stiffness transition Tunn. Undergr. Space Technol 77 103–114
[9] Lubliner J, Oliver J, Oller S and Oñate E 1989 A plastic-damage model for concrete Int. J. Solids and Structures 25 299-326

Acknowledgments
The research has been supported by the following projects: (1) Scientific research project of Shanghai Science and Technology Commission: Research on key technologies for industrialized construction of cut-and-cover tunnels design (17DZ1203402). (2) National Key Research and Development Program: Seismogenesis and Disaster Control of New Urban Underground Corridor Structures (2017YFC1500703). (3) Scientific research project of Shanghai Science and Technology Commission: Evaluation of seismic performance and safety control technology of super shallow shield tunnel (18DZ1205103). (4) National Natural Science Foundation of China: Evolution of Safety Performance and Intelligent Control of High-Speed Railway Tunnels in Service (U1934210).