Impact Analysis and Protection Scheme of Subway Shield Tunneling under Existing Railways

HE Zheng Hua¹, Wang Guo Quan², Chen Jian Wei², Zhang Xu Zhi³, Huang Yong⁴

¹ Central and Southern China Municipal Design & Research Institute Co., Ltd., Hubei Wuhan 430010, China
² Ningbo Urban Construction Design Institute Co., Ltd., Zhejiang Ningbo 315012, China
³ School of Civil Engineering, Central South University, Hunan Changsha 410075, China
⁴ Sinohydro Bureau 8 Co., Ltd., Hunan Changsha 410004, China

Abstract: The urban rail transit shield will have a bad influence on the railway’s safe operation when it tunnels under existing railways. Main measures to avoid risks include reasonable analysis of the influence of tunneling under existing railway subgrade, design of effective construction schemes and reinforcement of protection of existing railways. According to the case of engineering of Wuhan Metro Line 7 under the existing Wuhan-Guangzhou Passenger Railway, the influence of the metro tunneling project on the settlement of Wuhan-Guangzhou Passenger Railway subgrade is analyzed. In addition, precautions for the tunneling project and protection measures for the existing railways are proposed herein.

1. Introduction

The Wuchang-Rui’an section of Wuhan Metro Line 7 [1] stretches a total of 1514km from Wuchang Railway Station to Rui’an Street Station. Starting from Wuchang Railway Station, it runs southwards along the western side of Zhongshan Road, intersects with Line 4 at Wuchang Railway Station and proceeds through the underground space of the railway station’s Western Plaza; then it intersects the underpass of Zhongshan Road, runs under Chuxiong Avenue and through the pile foundation of Wuwuzhou Bridge, moving down under the Wuhan-Guangzhou Passenger Railway and residential areas of Jianghong Town to the southern end at Rui’an Street Station.

Built through shield tunneling, the tunnel in this section is structured by lining of circular segments which are 350mm thick and 1.5m broad, with the inner diameter at 5.5m and its outer diameter at 6.2m.

Wuhan-Guangzhou Passenger Railway Line 2 is a railway maintenance line between Wuchang Railway Station and Wuhan Rail Maintenance Station, structured by ballasted tracks and concrete crossties. With its track ballast full of crushed stones, this line is in good condition and trains that currently run on this line are relatively few.
2. Locational Interrelation

Wuchang-Rui’an section of Wuhan Metro Line 7 tunnels under the subgrade of Wuhan-Guangzhou Passenger Railway Line 2 twice, totaling 30m and at an angle of about 49° with the railway. The vertical distances between the tunnel’s top and the subgrade of Line 2 are 11.555m and 10.865m respectively [2]. The soil strata of the tunnels are the stratum of silty clay mingled with clay (3-2) and the clay stratum (10-2) [3]. Details are shown in Figures 1–5.
3. Numerical Analysis
To study the influence of shield tunneling on the existing railways [4], the software FLAC3D [5] is used to build a 3D finite-element model, as shown in Fig. 6. The model adopts normal constraints for the four horizontal directions, with fixed constraint at its bottom and free constraints on its top. The tunneling is simulated via the null element model while shielding via the activation element model.

All elements used in the model are solid elements. The beam element is adopted for rail crossties, the Mohr-Coulomb model for the structure of soil strata, and the elasticity constructive model for other elements [6].

The physical mechanical parameters are derived from the in-depth survey report, with details shown in the following tables.

### Table 1 Proposed Physical Mechanical Parameters of Soil

| Strata code | Soil                          | Natural Weight $\gamma$/kN/m$^3$ | Modulus of Compression $E$/(1-2)/MPa | Shear Strength Indicators | Frictional Angle $\phi$/° |
|-------------|-------------------------------|----------------------------------|--------------------------------------|--------------------------|------------------------|
| (1-1)       | miscellaneous fill            | 18.5                             | —                                    | 7~11                     | 17-21                  |
| (1-2)       | Plain fill                    | 18.3                             | 2.5-3.8                              | 11~15                    | 5-9                    |
| (10-2)      | clay                          | 19.6                             | 11.0-15                              | 37~42                    | 15-19                  |
| (18b-1)     | Intensely weathered silty mudstone | 21          | 32.0-42                              | 42~52                    | 15-19                  |
| (18b-2)     | Moderately weathered silty mudstone | —          | —                                    | —                        | —                      |

### Table 2 Parameters for subgrade and tunnel segment materials

#### A) subgrade materials parameters

| Supporting structure | Cohesion kPa | Internal friction angle | Poisson’s ratio |
|----------------------|--------------|-------------------------|-----------------|
| Subgrade fill        | 25           | 25                      | 0.2             |

#### B) tunnel segment materials parameter

| Supporting structure | Unit weight/KN/m$^3$ | Elasticity modulus/Gpa | Poisson’s ratio |
|----------------------|----------------------|------------------------|-----------------|
| Tunnel segment (C50) | 25                   | 27.6                   | 0.2             |

The analytical simulation of the tunneling project is conducted once, during which the values for displacement and ground settlement of Wuhan-Guangzhou Passenger Railway Line 2 are obtained and compared with the railway deformation standards to decide whether the values meet the requirements.
When the tunneling begins, the structural stress is released, leading to deformation and displacement of the tunnel and surrounding soil strata as well as certain influence on the structure of the existing railways. Fig. 7 and Fig. 8 presents the tendency maps of vertical displacements of soil strata and the railway structure after the tunneling projects begin.

In the first tunneling project, the largest displacement, about 10.8mm, occurs on the vault of the tunnel, and the largest value of ground settlement is 4.5mm; in the second tunneling project, the largest displacement is 9.147mm, also on the tunnel’s vault, and the largest ground settlement is around 2.7mm. Details are shown in Table 3.

| Rail monitoring location       | Maximum subsidence of left steel track /mm | Maximum subsidence of right steel track /mm | Difference value of settlement /mm |
|-------------------------------|-------------------------------------------|------------------------------------------|---------------------------------|
| Wuhan-Guangzhou Passenger Railway Line 2 | 2.6541                                      | 2.6815                                     | 0.0274                           |
| Left tunnel                   |                                            |                                           |                                 |
| Right tunnel                  | 2.3654                                      | 2.3344                                     | 0.031                            |
| Control Standard              | 9                                           | 9                                         | 5                               |

Figure 6. tunneling model of Wuchang-Rui’an section under the subgrade of Wuhan-Guangzhou Passenger Railway

Figure 7. tendency maps of displacement of Wuhan-Guangzhou Passenger Railway subgrade first underneath pass

Figure 8. tendency maps of displacement of Wuhan-Guangzhou Passenger Railway subgrade second underneath pass
Table 4 vertical displacement of Wuhan-Guangzhou Railway Line 2 second pass

| Rail monitoring location | Maximum subsidence of left steel track /mm | Maximum subsidence of right steel track /mm | Difference value of settlement/mm |
|------------------------|------------------------------------------|--------------------------------------------|----------------------------------|
| Wuhan-Guangzhou Passenger Railway Line 2 Left tunnel | 4.4943 | 4.4944 | 1.6E-04 |
| Right tunnel | 3.7567 | 3.7489 | 2.1E-03 |
| Control Standard | 9 | 9 | 5 |

To sum up, the shield-tunneling during the rail construction will influence the existing railways, but the values for vertical ground settlement and the difference values are controlled within the standard ranges, which means it is feasible to shield-tunneling under the existing railways’ subgrade. However, there are still risks in the construction process, and it is necessary to take safety-control measures and protect the existing railways to ensure smooth construction.

4. Protection schemes and construction measures

4.1. shield-tunneling measures

4.2. Rational analysis of the excavation parameters of the tunneling shields under the railways within 50m in front is conducted and the ground settlement is observed so as to determine the setting value of the soil pressure and soil dump rate during the excavation process. Meanwhile, the excavating speed is also decided to round out the excavation parameters.

4.2.1. During the excavation process, the surrounding soil properties have significant impacts on the soil chamber pressure, the excavation speed, the excavation force, the volume of excavated soil, the cutter’s rotation speed, the grouting volume, grouting pressure and others. Major improvement measures are as follows:

- control of the volume of removed muck: This means ensuring that the soil chamber pressure remains at a stable and balanced state with its fluctuations minimized; meanwhile, the volume of excavated soil is controlled within a proper range. According to relevant construction experience, the volume of removed muck is controlled and the stratum loss rate is no higher than 5‰.
- improvement of the muck: This means properly adding foaming agents and adjusting the volume of water used, with the volume controlled according to real situations.
- control of excavation speed: This is to select proper excavation speed through the experimental section. Also, during the tunneling process under the subgrade of Wuhan-Guangzhou Passenger Railway, the tunnels shall be excavated in an even manner and its influence on the land strata shall be minimized.

4.2.2. Quick excavation

Deformation of the wall rock plastic zone in the tunnel features hysteresis, so before the wall rock plastic zone fully develops, the excavation shall be fulfilled as quickly as possible under the premise of a constant speed. At the same time, grunting of the soil strata needs to be reinforced in time to avoid ground settlement above the tunnel. The specific measure is to complete installation of tunnel segments quickly.

- Strict control of excavation attitude. In the excavation process, the line and attitude of the tunnel shall be under strict control to reduce or eliminate deviation. To minimize its influence on the subgrade of Beijing-Guangzhou Railway, the attitude shall be controlled within ±5mm.
- Strict control over the volume of synchronous grouting and second grouting as well as the grouting pressure. Overpressure of synchronous grouting and second grouting shall be avoided.
In light of the actual conditions of the land strata, it shall be ensured that the volume of synchronous grouting under the subgrade of Wuhan-Guangzhou Passenger Railway is no lower than 150%.

- Construction management shall be strengthened during the tunneling projects. The soil chamber shall remain unblocked during the tunneling projects under the subgrade of Wuhan-Guangzhou Passenger Railway to avoid mismanagement-induced emergencies.
- Management of the tail part of the tunneling shields shall be reinforced during the tunneling project under the railway subgrade. During the excavation, the tunnel tail brush shall be properly protected to avoid insufficient oil injection and it shall be made certain that there is no grout leakage before the tunneling.
- The existing tunnel segments shall be reinforced before the tunneling projects began to ensure structural safety of the metro when the newly constructed tunnels are put to use.

4.2.3. Protection schemes for tunneling under the subgrade of Wuhan-Guangzhou Passenger Railway

Based on the conclusions above and in light of prior successful tunneling experience in other regions around China, the following measures are proposed for the tunneling projects under Wuhan-Guangzhou Passenger Railway.

- Control the train’s speed when it is passing the section of the tunnel concerned: the train shall pass the section of the tunnel concerned slowly at a speed lower than 45km/h. Besides, as the section of the tunnel concerned is about 1.1km away from Wuchang Railway Station, trains which are not scheduled to stop are supposed to pass at a slow speed as well.
- Adjust the rail fasteners: the adjustment range shall be controlled within 10mm.
- Prepare emergency precautions to prevent major ground settlement of the railway during the tunneling projects: the grouting tubes shall be arranged evenly every two meters along the tunnel and be slanted to the subgrade of the railways. Also, to avoid accidents during excavation, it shall be made certain that there will be timely grouting of cement plasters to make up the soil bearing capacity when major ground settlement or other dangers occur.

5. Conclusions

To tunnel under the existing railways may incur danger to the existing railways, and based on analysis of tunneling projects of Wuchang-Rui’an section of Wuhan Metro Line 7 under Wuhan-Guangzhou Passenger Railway, this paper reached the following conclusions:

- According to the analysis of the influence of the tunneling projects on the subgrade of Wuhan-Guangzhou Passenger Railway by finite-difference analysis software, the strata that the tunneling shields perforate under Wuhan-Guangzhou Passenger Railway consist of the stratum of silty clay mingled with clay and the clay stratum, the deformation of which is controllable and thus meets relevant standards.
- Major tunneling solutions and protection measures for the existing railways are proposed, and when implemented, these solutions and measures will ensure the projects’ smooth progress. So far, the tunneling shields for Wuchang-Rui’an section have perforated the subgrade of Wuhan-Guangzhou Passenger Railway Line 2 successfully.

6. Reference

[1] Wang Tao. Research on Evaluation Methods for Urban Rail Transit Construction Projects[J]. *Journal of Railway Engineering Society*, 2011, 28(04): 88-93. [2017-09-26].
[2] FANG Yong, He Chuan. Analysis of Influence of Undercrossing Subway Shield Tunneling Construction on the Overlying Tunnel [J]. *Journal of railway*, 2007, (02): 83-88.
[3] Zou Chaoyang. Discussion on Technica Measures of Xuzhou Metro Line 2 under Passing Existing Beijing-Shanghai Railwag Line[J]. *Modern Urban Transit*, 2017(04): 29-33.
[4] Dai Yifei, Sun Lei, Zhang Wei. Numerical Analysis of Existing Tunnel Under crossed by Shield Tunnel in Short Distance [J]. Soil Engineering and Foundation, 2012, 26(02): 13-15.

[5] Hua Zhou, Xiao Tao Wu, Dong Ni Zhou, Tian Tian. A Coupling Modeling Method with ANSYS/FLAC3D and its Application [J]. Applied Mechanics and Materials, 2012, 1800(170).

[6] Hao Wang, Zi Xiong Chen, Dong Ming Zhang. Rock Slope Stability Analysis Based on FLAC3D Numerical Simulation [J]. Applied Mechanics and Materials, 2012, 1800(170).

[7] Fu Jianghua. Settlement influence and control study of shield traverses the existing high-speed rail [J]. China Water Transport, 2015, 15(12): 244-246.

[8] Zhao Qiangzheng. Study on Effects of Metro Shield Tunnel Crossing Under Highway Tunnel and Building Foundation [J]. Transportation Science & Technology, 2013(3): 106-108.