Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)

Shield tunneling beneath existing railway line in soft ground

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ABSTRACT: The paper discusses the geodynamic challenges and technical countermeasures in the shield tunnel projects passing under an existing railway line, especially for soft ground conditions. Three main issues needed to be solved by the engineering community: train safety during the period of tunnel construction, accelerated track degradation of track structure in the long term and tunnel structure durability. This paper describes and predicts the nature of the three issues, the countermeasures are also given.

1 INTRODUCTION

Cities and urban population steadily grow, and put stringent requirements for metro transportation. With the development of the metro system, more and more metro tunnels need to pass under an existing railway line, such as metro line 9, 11 and 7 in Shanghai, China. At the same time, the railway lines have been speeded up and are planned for increasingly higher train speeds and higher loads, while existing lines need to be upgraded to allow faster, heavier and more frequent trains. In this context, three main issues need to be considered:

1. The "Train Safety" issue: excessive settlement of the track due to the tunnel excavation must be avoided to ensure the permissible deviations in track geometry.
2. The "Track Structure Durability" issue: increasing traffic density, loads and metro tunnel structure bring about higher dynamic actions and more intensive track maintenance.
3. The "Tunnel Structure Durability" issue: dynamic actions are to be sustained by tunnel structure.

This paper discusses these issues in Shanghai, China. The train safety issue and countermeasures during the metro tunnel construction are concentrated.

2 SITE DESCRIPTION

The site chosen for the project was the Jiading area in Shanghai, where metro line 11 passes under Hu-Ning railway Line. Figure 1 shows their plane and vertical position. The angle between them is 85 degree, almost perpendicular. The overburden soil depth of shield tunnel is 11.08 m, its outside diameter is 6.2 m and the thickness of tunnel lining is 0.35 m, the groundwater level is about 1m below the ground surface.

Table 1. Soil parameters.

Parameters	Soil layer ②$_1$	②$_2$	③$_1$	⑤	⑥
Gravity (γ) (kN/m^3)	18.4	18.1	17.4	17.7	19.3
Cohesion C(kPa)	13.0	8.0	9.0	13.0	45
Angle of friction Φ(degrees)	18.5	24.0	17.0	13.0	15
Lateral ratio of earth pressure K_0	0.46	0.41	0.50	0.50	0.40
Compressive Modulus (MPa)	5.25	7.22	5.50	6.77	10.5

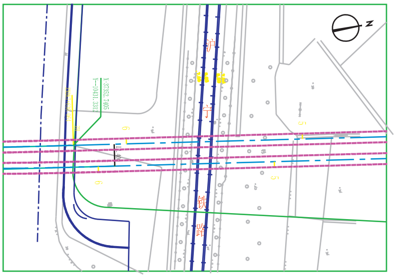
* In Table 1, ②$_1$ is Tan silty clay, ②$_2$ is Sallow silty clay, ③$_1$ is grey silty clay, ⑤is grey clay, ⑥is Sap green Clay.

The 4.5 m high embankment of Hu-Ning railway line has been constructed in 1908. The train speed have increased up to 250 km/h at 18th, April, 2007 and demands for shortening travel times are rising. Figure 1(b) also shows the geological profile of the chosen site, the soil properties are in table 1. According to the geotechnical investigation, the site can be characterized by a 1.5 m weathered crust over a layer of soft clay with a thickness of about 13.0 m. Under these layers lies silty clay whose stiffness is more greater than the overlying soils.

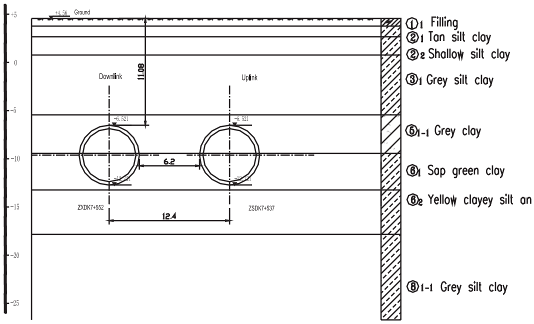
Track-side buildings are almost not existing, so the influences on environment can be ignored.

3 THE SAFETY OF RUNNING OF THE TRAINS DURING TUNNEL EXCAVATION

Tunnel excavation may induce adverse effects on nearby existing structures and services (e.g., deformation on tracks, derail of trains). The accurate prediction



(a) Plain position



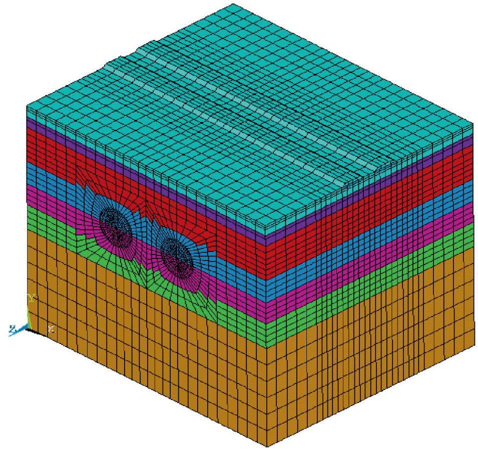
(b) Geological profile

Figure 1. Layout of railway line and shield tunnel.

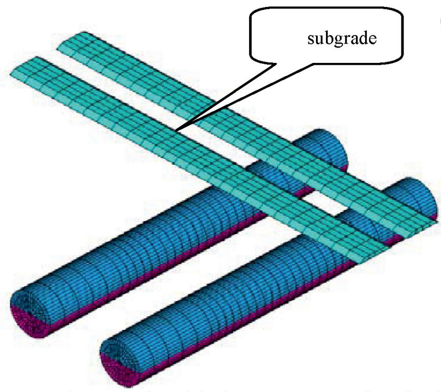
of tunneling effects poses a major challenge during design.

The effects of tunnel advancement during construction on the ground and railway track are three dimensional and transient. In this paper, a 3D, elasto-plastic analysis was performed. Figure 2 shows the 3D finite element mesh. The mesh was 50 m long, 45 m wide and 40 m high. Eight-node brick elements and four-node shell elements were used to model the soil and the concrete lining, respectively. Roller supports were applied on all vertical sides of the mesh, whereas fixed supports were assigned to the base of the mesh. Therefore, the movement normal to all vertical sides of the mesh and the movement in all directions at the base of the mesh were restrained. The water table was located at the ground surface. An elasto-perfectly-plastic soil model using the Mohr-Coulumb failure criterion with a non-associated flow rule was adopted in this study. The tunnel lining was modeled as a linear elastic material. The Young's modulus and Poisson's ratio for the tunnel lining were taken as 30 GPa and 0.3, respectively. The unit weight of the tunnel lining was 24 kN/m^3.

Figure 3 shows the progressive changes in the tunneling-induced surface settlement under the track as the tunnel advances. With further excavation, the surface settlements continue to increase. Considering the tunneling-induced deformation, the irregularity of the track is shown in Figure 4.



(a) Whole model



(b) Location relationship between tunnel and railway

Figure 2. Finite element mesh.

The derail coefficient and rate of wheel load reduction were shown as table 2 using locomotive-track dynamic coupling model. According to the protocol published by the Ministry of Railway in China, the stability and safety of the train will be threatened if the running speed of train is above 100km/h (passenger car) and 60 km/h (freight), so the train speed must be limited during the tunnel construction.

3.1 *Influence on tunnel lining by running trains*

After the construction of the tunnel, the dynamic stresses induced by a running train will act on the tunnel lining for a long time, even until the railway line or the metro line will be abandoned. So the influence of the dynamic stresses must be considered. In general, the dynamic stresses induced by a train running dissipate quickly because of the nonlinear material and the viscous damping. The influence depth is only about 3m under the sub-grade bed. But the values of dynamic stresses will be greater with the tunnel under

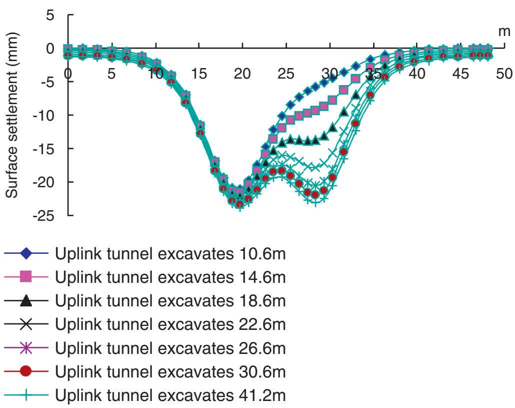


Figure 3. Tunneling-induced surface deformation.

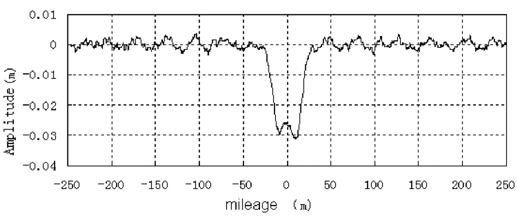


Figure 4. Longitudinal irregularity of the tracks by tunneling-induced deformation.

Table 2. Maximum value of derail coefficient and wheel load reduction.

Vehicle		Passenger car				Freight			
Speed (km/h)		90		100		50		60	
Item		①	②	①	②	①	②	①	②
Pair of wheels	I	0.63	0.13	0.75	0.20	0.69	0.21	0.98	0.25
	II	0.51	0.10	0.59	0.13	0.56	0.15	0.78	0.22
	III	0.48	0.08	0.56	0.11	0.53	0.15	0.75	0.20
	IV	0.60	0.11	0.73	0.21	0.67	0.19	0.93	0.23

*In Table 2, ① represents Derail coefficient, ② represents wheel load reduction.

the railway line, because the stiffness of tunnel is much greater then the soft soil at the same depth.

The dynamic stresses acting on tunnel lining have been established using a dynamic numerical model. Laboratory tests have shown that soil stiffness and damping change with cyclic strain amplitude under dynamic cyclic loading conditions. To simplify, the soil is modeled using equivalent Linear analysis, the damping ratio also changes with strain. Figure 5 shows the loads acting on the tunnel lining including the

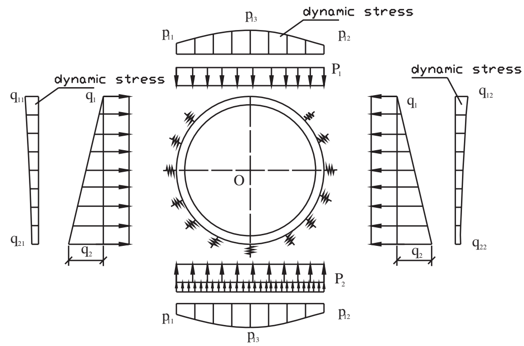


Figure 5. Load-structure model including dynamic stress.

dynamic stresses. It is quite different from the conditions with only static stresses. The long-term actions of dynamic stresses will influence the service life time of tunnel structure.

4 SAFETY COUNTERMEASURES

4.1 *Countermeasures to ensure the train safety during tunnel excavation*

There are basically three ways to decrease the influence on safety of the trains during tunnel construction: (a) by decreasing the tunneling induced deformation; (b) by increasing the longitudinal bending stiffness of track structure itself; (c) limit the running speed of the train.

Decreasing the tunneling induced deformation may for instance be done by means of improving the stiffness and strength of the soil around the tunnel. This can be done by for example lime-cement piles, jet-piles or other deep-mixing methods. These countermeasures are easier to implement as part of the foundation work of new lines, than as a retrofitting method under existing lines.

Figure 6 shows the reinforcing areas and methods around the tunnel, including jet-piles and grouting. These countermeasures decrease the track deformation during the tunneling. The value of the settlements is only 15% of the original deformation, so the remaining track irregularity is small. At the same time, the bearing capacity of the foundation of the railway track after the tunnel construction will increase.

The construction parameters should be controlled during the metro tunnel excavation to decrease the disturbing of the soil. Table 3 shows the recommended parameters. The controlling and monitoring systems should also be perfect to follow the track deformations. Figure 7 shows the measured deformations at the site during tunnel construction. ① is the preliminary settlement, ② is the settlement induced by shield arrival, ③ is the settlement during tunnel construction, ④ is the

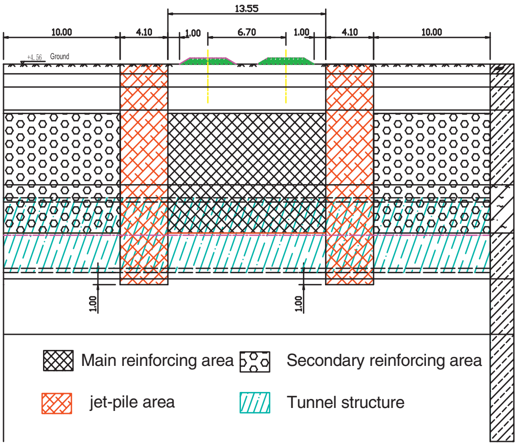


Figure 6. Reinforced soil around the tunnel.

Table 3. Construction parameters.

Construction parameters	Construction site Hu-Ning Railway
Support pressure (MPa)	0.20～0.22
Grouting pressure (MPa)	0.19～0.21
Grouting amount (m^3)	3.3～4.1
Grouting speed (L/s)	1.1～1.4
Construction speed (cm/min)	2.0～2.5

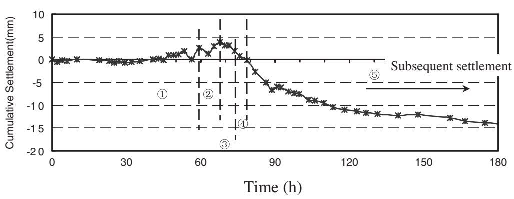


Figure 7. Measured deformation at the site during tunnel construction.

settlement induced by sub-optimal filling of shield's rear, ⑤ is the subsequent settlement. The results show that the deformation of the track has been controlled effectively. These approaches can be used.

4.2 *Countermeasures to protect the tunnel lining*

Considering the long life time and the exhausted strength, the lining stiffness and strength should be increased. So the reinforcement ratio of the tunnel lining under the railway line has been increased.

5 CONCLUSIONS

Tunnels passing under an existing railway line must ensure the train safety, the track structure durability and the tunnel structure durability. These problems are especially important in soft ground areas. In order to decrease the dynamic stresses acting on the tunnel lining, to decrease the tunneling induced deformation, and to even increase the bearing capacity of the ground, the soft soil and tunnel lining stiffness must be reinforced.

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REFERENCES

Esveld, C. 1989. Modern Railway Track. MRT-Productions, ISBN 90-800324-1-7.

Esveld, C. 1997. Innovation for the control of infrastructure maintenance. *Rail International/Schienen der Welt.*

Suiker, A.S.J. 1996. Dynamic behaviour of homogeneous and stratified media under pulses and moving loads. TU Delft, Report 7-96-119-1.