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Effect of the excavation clearance of an under-crossing shield tunnel on existing shield tunnels

Minglun Yin[a], Hua Jiang[a,*], Yusheng Jiang[a], Zhengyang Sun[a], Quanli Wu[b]

[a] School of Mechanics and Civil Engineering, China University of Mining & Technology, Beijing, Beijing 100083, PR China
[b] China Construction Communications Engrg. Group Corp. Ltd., Beijing 100161, PR China

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ABSTRACT

The excavation by earth pressure balance (EPB) shield could cause stress fields varied, which is harmful to adjacent existing structures. Thus the effect of excavation clearance of the EPB shield on the settlement of existing structures should be taken into account. The transit tunnel from Meicun to Shangmeilin of Shenzhen Metro Line 9 constructed by the EPB shield with mid-shield-grouting was investigated. The deformation of existing tunnel is analysed by three-dimensional (3D) finite element methods (FEM). It is found that the settlement of overburden soil is obviously influenced by the structure of the existing tunnels through the plastic development of the soil. The rate of settlement is remarkable when the shield effect zone approaches the existing tunnels so that timely mid-shield grouting is an efficient method of controlling the settlement induced by the excavation clearance. However, the grout used in this method should be with the properties of short hardening time, large elastic modulus and low shear strength. Different standards of settlement control should be employed with respect to different underground tunnels, in which minimum elastic modulus of the filler that is usually determined by fitting function. This can be taken as a guide rule of the selection of material parameters in the project. The simulation results are in good agreement with the settlements measured for the existing tunnels and the ground surface. The parameter sensitivity analysis by means of the Spearman's correlation coefficients shows that the elastic modulus of filling material significantly influences on the settlement of the existing tunnels and the ground surface.

1. Introduction

China is one of fastest growing urban rail transport networks in the world. By the end of 2016, there were 134 metro lines in operation with a total mileage of 4153 km in 30 cities according to the statistics. More than 400 metro lines, with more than 15,000 km total mileages, are in planning. With the development of urban rail transit construction in China, the scale of urban underground space development and utilization is expanding.

In practical engineering, empirical methods are generally used to predict ground settlement induced by tunnel construction. Peck (1969) illustrated that the transverse settlement trough induced by a tunnel can be fitted by a Gaussian function. This function is widely accepted in the tunnel industry although it has no theoretical background. Loganathan and Poulos (1998) stated the limitations of empirical methods, such as the applicability to different ground conditions, tunnel geometries and construction techniques and limited information about the distribution of settlement, and proposed a method of predicting tunnelling-induced settlement and horizontal movement of the ground. Zhu et al. (2014) analysed the ground movement induced by tunnel construction in sand considering an excavation disturbance. Klop and Logar (2014) investigated the effect of overburden above the tunnel and the influence of the orientation of anisotropy plane on the surface settlements. Zhou et al. (2017) developed and employed a random forest to predict ground settlement above tunnels.

With the rapid development of advance technology, numerical modelling has been widely applied to simulate the behaviours of underground engineering under different loading and environment conditions. Gioda and Swoboda (1999) indicated that numerical methods can be used to solve tunnelling engineering problems, in which non-homogeneous initial stress distribution, non-linear and time-dependent, and multi-physical fields can be considered. Li et al. (2010) studied the interaction between parallel twin shield tunnels in several 3D numerical simulations. Valizadeh Kivi et al. (2012) analysed the settlement caused by the construction of railway station employing the central beam column structure method and the finite element analysis software ABAQUS. Wang et al. (2012) investigated the failure mechanism for a circular tunnel in transversely isotropic rock by realistic failure process

* Corresponding author.
E-mail address: alandavidrain@163.com (H. Jiang).

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analysis. Do et al. (2014) studied the effect of the construction process between two tunnels using FLAC3D software. Das et al. (2017) analysed the stability of two asymmetric tunnels opening at shallow depth to address the influence of topography, twin tunnel dimension and geometry. Michael et al. (2017) simulated important components of the mechanised excavation process and compared three lining models based on the FEA software ABAQUS.

In recent years, shield tunnel construction adjacent to existing underground structures has been encountered frequently. The safety of existing underground structures and a newly-built shield tunnel largely depends on the proper control of tunnelling-induced settlement. Therefore, many more studies have been focused on the effects of tunnel excavation on adjacent existing structures (Amir and Vojtech, 2017; Liang et al., 2017, 2016; Sze et al., 2016; Zheng et al., 2018). Mirhabibi and Soroush (2013) investigated the effect of twin-tunnelling-induced ground settlement on existing buildings by 3D FEM. Chakeri et al. (2011) studied the characters of deformation, stress distribution, and surface settlement during the construction of twin Tohid Tunnels undercrossing the Line 4 metro tunnels in Tehran. Zhang and Huang (2014) presented the shield construction of up-crossing and under-crossing tunnels by both 3D FE simulation and simplified analytical method. Fang et al., (2015) analysed a case of closely spaced twin tunnels excavated undercrossing other existing twin tunnels in Beijing, China. Bilotta et al. (2017) calibrated a 3D FEM model to analyse a stretch of a tunnel under construction in Napoli, Italy.

Ground settlement is unavoidable during tunnel excavation owing to the excavation techniques of the earth pressure balance (EPB) shield. The traditional grouting theory deems that continued grouting directly into the tailskin clearance with a certain pressure can meet the settlement control requirements. Most previous studies focused on the settlement induced by tailskin clearance between shield and segments. Generally, synchronous grouting and replenishing grouting are applied to fill the tailskin clearance in order to control ground deformation (Youn and Breitenbücher, 2014). However, less attention has been paid to the excavation clearance between soil and shield after excavation. The tailskin clearance and excavation clearance are illustrated in Fig. 1. And Fig. 2 shows the cross section of the excavation clearance.

If the tunnels and the adjacent structures are in stable soil layers and require low settlement standards, then the deformation induced by excavation clearance would be negligible. Under other circumstances such as tunnelling in sensitive soil or an area with major risks, the above-mentioned deformation may be beyond control. In view of these problems, cement grouting is usually adopted for ground reinforcement. However, such reinforcement scheme may be probably limited by the site construction conditions and cost. Another method is to enhance the amount and pressure of synchronous grouting, with proper replenishing grouting. However, the high pressure could increase the stress in segments and the higher probability of segment damage.

As the underground space environment becomes more complex,

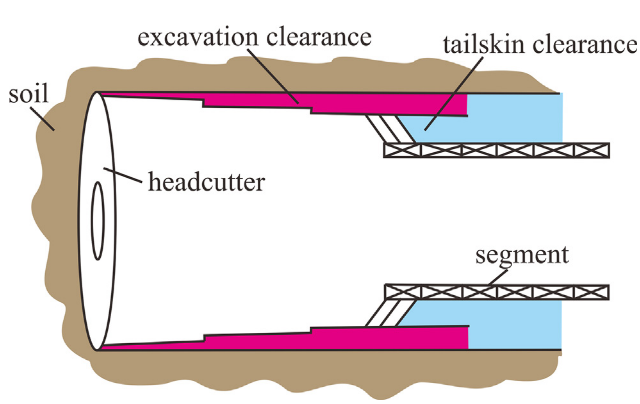

Fig. 1. Longitudinal section of the shield excavation.

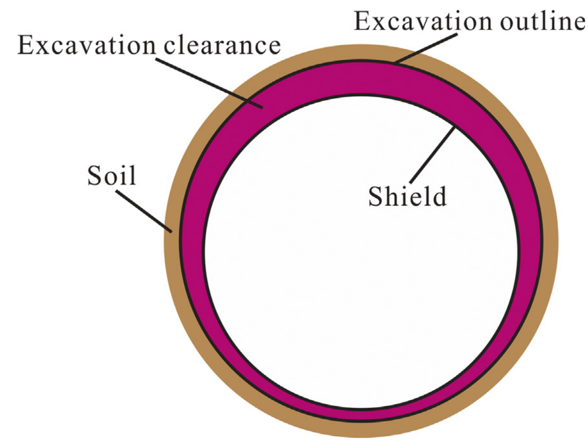

Fig. 2. Cross section of the excavation clearance.

disturbances to the surrounding soils due to tunnelling need to be minimized by further improvement in the production technology of shield construction.

The synchronous grouting is usually used to fill the gap between segments and soils during shield excavation. However, the excavation clearance is not filled. Kasper and Meschke (2006) modelled the material behaviour of saturated soil and synchronous grout by a two-field FE formulation in conjunction with the cam clay constitutive model for soil and a hydration-dependent model for grout. Youn and Breitenbücher (2014) studied the parameters of the grout mixtures on the properties of the synchronous grout in shield tunnelling. Mechanical properties of two component grouts such as compressive strength, elasticity modulus and Poisson's ratio were studied by Sharghi et al. (2017). Shah et al., (2018) studied on a two-component grout composed of a chemically retarded cement slurry and an accelerator, which was pumped into the annular clearance behind the TBM shield. It should be noted that the effects of excavation clearance between the existing structures and soil are ignored in traditional grouting theory. Thus, the traditional method cannot meet the rising demand for deformation control. Based on the above background, the mid-shield grouting method is proposed for better deformation control during EPB shield tunnelling.

The mid-shield grouting method involves injecting the filling material into the excavation clearance through grouting pumps while excavating the shield. It is easy to reduce the stress release for early supporting measure compared with the traditional supporting, which is particularly convenient to deal with the major risk projects.

The mid-shield grouting system mainly consists of tanks, grouting pumps, electromagnetic flowmeters and pressure gages (Fig. 3). Before grouting, materials such as cement and water are mixed with a certain proportion in two different tanks to make Grout A and Grout B. Two grouting pumps pump Grout A and Grout B from two tanks and then transport them into the nearby reserved grouting hole through grouting pipes. Electromagnetic flowmeters and pressure gages are installed in the pipelines to monitor the amount and pressure of grouting. Subsequently, Grout A and Grout B are mixed at a tee-junction, where another pressure gage is installed. Finally, the mixed grout is injected into the excavation clearance.

Particularly attention has been paid to the grout that the mid-shield method is different from the traditional single-fluid or cement and sodium silicate mixed grout. On the one hand, single-fluid grout, also known as cement paste, need a long time of coagulation. The single-fluid is thus inappropriately considered as grouting fluid because support effect cannot be triggered in a short time. On the other hand, even though cement and sodium silicate mixed grout is with the character of rapid-hardening, high shear strength could result in the shield locked. In fact, the grout used by the mid-shield grouting method could be