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Effects of lateral unloading on the mechanical and deformation performance of shield tunnel segment joints

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ABSTRACT

Unloading during lateral excavation widely occurs in existing subway shield tunnels. Previous studies have focused on the overall stress and deformation of existing tunnels caused by nearby unloading. However, the stress and deformation state of tunnel segment joints have yet to be considered. This study considered the non-continuity of the shield tunnel lining and the interactions among tunnel segment, surrounding rocks and ballast bed. A hybrid model of a shield tunnel was established based on 3D nonlinear contact theory. The mechanical and deformation properties of the segments and joints of an existing shield tunnel under the influence of lateral excavation of the foundation pits were studied. Unloading during lateral excavation caused the cross section of the shield tunnel to generate vertical convergence and shift horizontally towards the foundation pit. An opening and dislocation in the joint, which caused the waterproof ability of the joint to decrease sharply, were observed. Meanwhile, stress at the segment joint increased sharply and caused local cracks in the segment lining. Axial and shearing force on the joint bolt also increased significantly. Based on existing subway regulations, the calculation results were combined to establish a deformation control standard for existing shield tunnels under lateral excavation. The rate of vertical convergence of the lining should be less than 3.68‰, and the rate of horizontal shift of the axis should be less than 0.53‰.

1. Introduction

In recent years, many underground structures have been built in the urban environment, a development that often involves constructing new structures near existing metro tunnels. Engineering constructions, such as foundation pit excavation and tunnel and building construction around metro tunnels, are bound to cause adjacent ground areas to generate unloading and deformation, which tend to change the stress and deformation state of existing shield tunnels. Such change will in turn affect the service performance of existing subway tunnels. Chang et al. (2001) reported that a section of a tunnel in Taipei was damaged by a nearby excavation.

To avoid any damage to existing tunnels during and after excavation of new structures, various approaches have been used to study the interaction of new excavation and existing tunnels. Several semi-empirical or analytical methods were first proposed to evaluate the impact of excavation on existing tunnels. Ji and Liu (2001) deduced a simplified and versatile method, namely, Residual Stress Method, to calculate tunnel movements induced by adjacent excavation. Huang et al. (2006a) proposed a semi-experiential formula based on elasticity theory. Zhang et al. (2013a) presented a simplified analytical approach to analyse the deformation response of tunnels to excavation-induced soil unloading. Zhang et al. (2013b) presented a semi-analytical method to evaluate tunnel heave induced by adjacent excavation and verified the method with field measurement results. To ensure construction safety and optimise construction procedures, a series of experimental model tests and field measurements were then performed. Kim et al. (1998) performed physical tests to investigate the response of the first tunnel lining on the approaching second shield. The results of their model tests showed that the interaction effects are greater in the spring line and crown of the existing tunnel. In Choi and Lee (2010), the influence of the size of an existing tunnel, the distance between tunnel centres and the lateral earth pressure factor on mechanical behaviour of the existing and new tunnels were investigated. The numerical method can simulate the tunnel–soil interaction under complex conditions. It is also widely used to predict the stress and deformation of an existing tunnel under a nearby new excavation. By using the FLAC3D program, Do et al. (2014) investigated the structural forces induced in two tunnels and the development of the

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displacement field in the surrounding ground when a new tunnel is constructed near an existing tunnel. Karakus et al. (2007), Hage Chehade and Shahrour (2008), Chakeri et al. (2011), Liu et al. (2011b), Hasanpour et al. (2012) and other researchers conducted numerical analyses to study the influence of nearby tunnel construction on existing tunnels.

Most existing studies focused on the influence of nearby excavation unloading on the overall stress and deformation of shield tunnels. An equivalent model was usually used to calculate the results. However, the effects of excavation on segment joints were not considered. The lining of a shield tunnel is assembled by segments and has a large number of joints. Segment joints are the weakest part of a shield tunnel. Hence, the stress and deformation of a shield tunnel lining are different from those of an integral tunnel. Nearby excavation unloading will not only cause the integral deformation of a tunnel, but will also generate openings and dislocations in segment joints. The contact stress of segment and bolt at the joint will increase sharply and cause the joint to weaken. Consequently, the long-term safety of the tunnel will be at risk. Therefore, variations in the stress and deformation performance of segment joints should be considered when studying the effects of excavation unloading on existing shield tunnels.

Several researchers have focused on developing numerical models for the segment joints of shield tunnels. The models for calculations are classified by joint evaluation as follows: simplified equivalent model, ring with multiple hinged joints model and beam-spring or beam-shell model. In the simplified equivalent model (Teachavorasinskun and Chub-uppakarn, 2010), a coefficient of effective ratio of bending rigidity is introduced to evaluate the rigidity of joints and a transfer ratio of bending moment is introduced. The coefficient value is mainly determined by experiences in consideration of joint performance test results and past project records. In the ring with multiple hinged joints model (Zhong et al., 2006; Yang and Wang, 2012), segment joints are treated as hinges; the influence of girth joints are not considered but that of longitudinal joints is exaggerated. In the beam-spring or beam-shell model (Klappers et al., 2006; Huang et al., 2006b; Do et al., 2013; Li et al., 2014; Wang et al., 2014), a segment is considered a curved (straight) beam or a shell, and a segment joint is a rotational or shear spring. This model can reflect the more practical stress of the shield segments compared with the other models. However, simulating the interaction between segment joints is difficult, especially when demonstrating the opening and dislocation of joints under the effect of lateral unloading.

The current study takes the lateral excavation of a foundation pit as an example to investigate the deformation and stress of the segment joint of a subway tunnel under lateral unloading. The width, depth and length of the foundation pit are 22, 18 and 48 m, respectively (Fig. 1). The continuous underground wall with a thickness and total depth of 1.0 and 36 m, respectively, serves as the building envelope of the foundation pit. The foundation pit is excavated in six layers. The excavation depth for each layer is 3 m, and a steel tube is used as transverse bracing. The diameter of the steel tube is 609 mm, and the thickness is 16 mm. Horizontal distance and lateral distance of the transverse bracing are 2.2 and 3.0 m, respectively. Buried depth of the existing subway tunnel is 12 m. The trend of the tunnel is parallel to the length direction of the foundation pit, and the distance between the tunnel and foundation pit is 6.0 m.

The rest of the paper is organised as follows: Section 2 introduces the 3D discontinuous contact model, multi-scale modelling method and computation parameters. Section 3 presents and discusses the lateral excavation effects on the segment joint of a subway tunnel. Section 4 proposes a deformation control standard for an existing shield tunnel under the condition of lateral excavation. Finally, Section 5 summarises the conclusions of this research.

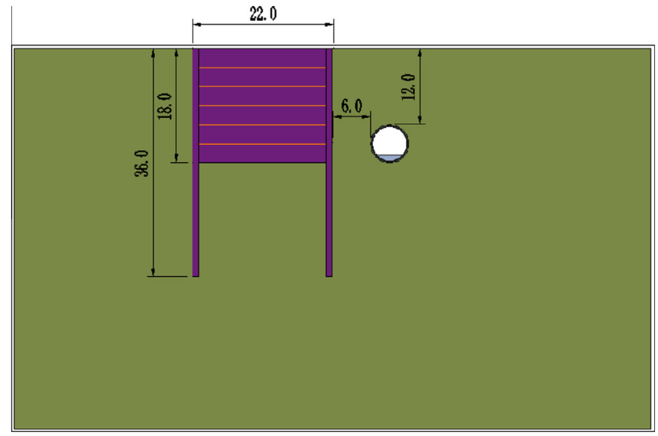

Fig. 1. Geometry and location of the foundation pit and the tunnel (m).

2. Computation and modelling method

2.1. 3D discontinuous contact model

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The shield tunnel is formed by assembling segments. Each segment is affected mutually at the joint. The interaction between joints is a complex contact action. The differences between the 3D discontinuous contact model and other calculation models is the setting and description of these contact relationships.

The entire calculation model is shown in Fig. 2. The model uses a stratum structure method, and its width, depth and length are 100, 60 and 50 m, respectively. In the model, the segment is simulated by using the solid element. Segment caulking and ethylene propylene diene monomer (EPDM) elastic rubber sealing gasket are considered in the calculation. The EPDM elastic rubber sealing gasket is simulated with the hyperelastic solid element. The beam element is used to simulate the segment bolt. The cross section is a circle with a diameter of 27 mm, and the actual length of the bolt is adopted. The bolt preload is considered to simulate the state of the joint under the connection of high-strength bolts. The preload is 30 kN according to the actual field condition. The ballast bed, surrounding rock mass and building envelopes are all simulated by using the solid element. This model sets corresponding direction constraints on the underside, left- and right-side face and front and back face.

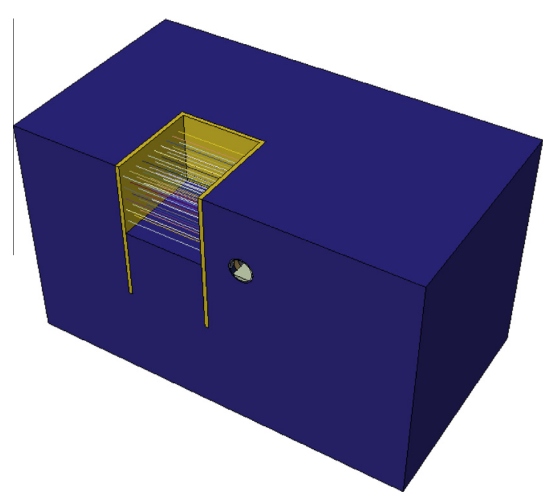

Fig. 2. Integrity of the calculation model.