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Research Paper

Simplified analytical method for evaluating the effects of adjacent excavation on shield tunnel considering the shearing effect

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ABSTRACT

Adjacent excavations may have adverse impacts on the existing tunnels. Due to the increasing demand for building excavations in close proximity to existing metro tunnels, ensuring the safety and integrity of tunnel structures is a major challenge for city designers and geotechnical engineers. Urban metro tunnels in soft areas of Chinese cities are often constructed using shield tunnelling technology, and the installed precast reinforcement concrete segmental lining are generally connected together by various steel bolts. Due to the presence of joints, the overall tunnel stiffness, including the bending stiffness and shearing stiffness, are significantly reduced. Due to the reduction in shearing stiffness, the tunnel longitudinal deformation can be decomposed into two distinct modes: a bending mode and a shearing dislocation mode. However, current methods for predicting tunnel longitudinal responses to adjacent excavations generally simplify a tunnel as an Euler-Bernoulli beam, which only considers the bending effect and ignores the shearing deformation of jointed tunnels. Moreover, tunnel-ground interactions are commonly considered through the Winkler foundation model, which is unable to account for the interactions of adjacent springs and leads to overestimations of shear forces and bending moments in shield tunnels. In this paper, a new analytical method is proposed that uses a Timoshenko beam to simulate jointed shield tunnel responses when subjected to an adjacent excavation, which can consider both the bending and shearing effects of a shield tunnel. The tunnel-ground interaction is considered by introducing Pasternak two-parameter foundation, which is able to further take account for the interaction between adjacent springs. The tunnel-excavation interaction is analyzed using a two-stage analysis method. First, the excavation-induced unloading stress on the existing tunnel is computed using Mindlin's solution. Second, the tunnel longitudinal deformation due to the corresponding stress is calculated using finite difference method. The effectiveness of the proposed approach is validated by two well-document case histories, including finite element analysis and field measurement. The predicted results are also compared with those obtained using the traditional methods. Based on the verified analytical solution, a parametric analysis is also conducted to investigate the effects of key factors on the responses of existing tunnels, including excavation-tunnel relative position, ground Young's modulus and equivalent shearing stiffness.

1. Introduction

To alleviate transportation stresses in large cities in China, many cities have been developing urban metro systems in recent decades. With the increasing development of China's economics, the commercial value of the metro systems has been widely recognized by city designers. Therefore, there is an increasing demand for construction commercial buildings near the metro tunnel lines. Excavation pits are generally constructed prior to main structure construction. The construction of excavation in close proximity to existing tunnel may cause a series of adverse effects on adjacent tunnels, including longitudinal differential deformation, leakage of groundwater, trail track distortion, and the separation between ballast-less bed and tunnel linings. To ensure the safety and integrity of metro tunnel structures are extremely important. If the excavation-induced interior forces exceed the capacity of a

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tunnel's structure, cracking may occur, and the safety of metro trains would be seriously threatened. A tunnel structure case history of damage in the Taipei metro tunnel project due to an adjacent excavation has been extensively reported by Chang et al. [1]. In this case, excessive displacement occurred in the nearby tunnel, and cracking in the segmental lining was obviously observed due to the large horizontal soil movement induced by the adjacent excavation. Thus, it is essential for all geotechnical engineers to assess the adverse effects of adjacent excavations on existing tunnels.

The interactions between the tunnel and adjacent excavations have attracted a large amount of academic attention. Many investigators have studied tunnel responses to adjacent excavations via case histories [1–4]. To fully understand the mechanisms of excavation-tunnel interactions, centrifuge modelling tests have also been carried out by researchers [5–7]. Numerical Finite Element Analysis has an advantage over other methods in modelling complex construction sequences and the non-linear interactions between the tunnels and the ground. Therefore, it is often used to simulate the interaction behaviours between tunnels and adjacent excavations. In the previous stage of study, as a result of limitations in computer computational abilities, two-dimensional analyses were carried out to investigate tunnel responses to excavations by ignoring the space-effect of excavations [8–11]. In reality, excavation-induced environmental impacts are typically three-dimensional problems [12]. Ignoring excavation-induced three-dimensional effects will lead to misleading results. In recent studies, three-dimensional finite element analyses were more frequently performed to explore the effects of existing tunnel due to adjacent excavation [12–15]. However, establishing numerical models is complicated, and the computation usually requires a lot of time, which is not convenient for geotechnical engineers when assessing the effects of tunnel.

In contrast to complicated Numerical Finite Element Analyses, analytical methods are computationally simple and can provide rapid predictions for the behaviours of existing tunnels due to excavations. At present, some analytical methods have been proposed to evaluate existing tunnel deformations subjected to adjacent excavations [16–18]. Zhang et al. [16] proposed a semi-analytical method to evaluate the heave of an underlying tunnel induced by an adjacent excavation. The influence of the excavation and the resistance of the tunnel were obtained based on Boussinesq's and Mindlin's solutions, respectively. The tunnel was assumed to be an elastic beam, and the rheologic deformation of the soil was also considered in their model. Zhang et al. [17] also presented a simplified analytical method using two-stage method. The tunnel was simplified as an Euler-Bernoulli beam resting on a Winkler foundation model. The excavation-induced unloading stress on the existing tunnel is computed using Mindlin's solution. Zhang et al. [18] proposed a simplified analytical method to calculate the tunnel/pipeline longitudinal responses due to an adjacent excavation disturbance. The tunnel was still assumed to be an Euler-Bernoulli beam, and the tunnel-excavation interaction was considered based on the Winkler foundation model.

By reviewing the literature, it was found at present that researchers have investigated excavation-tunnel interactions mainly through case histories, centrifuge modelling tests and numerical analyses, and few analytical methods have been presented for rapidly assessing excavation-tunnel interactions. Furthermore, in the presented analytical methods, shield tunnels are commonly simplified as Euler-Bernoulli beams, which only consider flexural deformation and overlook the shearing effect of shield tunnels. In addition, the Winkler foundation model has generally been used to simulate tunnel-ground interactions. However, due to the inherent discontinuity of adjacent springs, the model cannot reasonably represent the mechanical behaviours of foundation materials and often overestimates the bending moments of beams [19].

In this paper, a new analytical method for evaluating tunnel longitudinal deformations when subjected to adjacent excavation is proposed. First, the shield tunnel is simplified as a homogeneous Timoshenko beam, which is capable of taking into account both the bending and shearing dislocation effects of the shield tunnel structures. In addition, the tunnel-ground interaction is based on the Pasternak two-parameter foundation, which is able to consider the interaction between adjacent springs. The excavation-induced unloading stress on the existing tunnel is next calculated using Mindlin's solution. Subsequently, in this paper, a two-stage analysis method is adopted to analyze the excavation-tunnel interaction. The effectiveness of the proposed method is then validated by two well-documented case studies, including finite element analysis and field measurements. Based on the verified analytical solution, a parametric analysis is also performed to investigate the effects of influence factors on the behaviours of the shield tunnel due to the excavation, including the excavation-tunnel relative position, the ground Young's modulus and the equivalent shearing stiffness.

2. Tunnel and foundation model

2.1. Tunnel model

The metro tunnels in soft areas in China are generally constructed using Earth Pressure Balance (EPB) shield machine. The tunnel linings are comprised of several precast reinforcement concrete segments, which are connected by steel bolts. Unquestionably, the joint between adjacent segments is the weakest part of the tunnel structure, and it will inevitably affect the deformation mechanisms of the tunnel lining. Fig. 1 illustrates the deformation modes of tunnel structures. Shen et al. [20] and Wu et al. [21] both indicated that tunnel longitudinal deformation can be decomposed into two distinct modes: (a) a bending mode in which the segmental rings rotate around the center of the deformation curve and (b) a dislocation mode in which differential settlement of shield tunnel accumulates from the dislocation between rings, as illustrated in Fig. 1. Obviously, the two deformation modes are induced by the bending moments and shear forces along the longitudinal direction. Because of the joints between adjacent rings, the deformation mechanisms of a jointed shield tunnel are obviously different from those of a continuous tubular structure. For the latter, only the bending deformation mode occurs. However, for shield tunnels whose shear stiffness in circumferential joints is relatively low, shearing induced dislocations between adjacent rings occur. However, the previous studies [16–18] have mainly focused on the bending mode or the flexural deformation of tunnels by treating tunnels as continuous Euler-Bernoulli beams and neglecting the shearing-induced dislocations between adjacent segmental rings along the tunnel longitudinal direction.

Fig. 2a shows the deformation characteristics of an Euler-Bernoulli beam. The hypothesis of an Euler-Bernoulli beam is that the plane section remains plane and is still perpendicular to the neutral axis after deformation. This hypothesis neglects the shearing deformation of the beam and can only consider the flexural deformation. Apparently, the adoption of an Euler-Bernoulli beam for simulating a tunnel's structure can only take into account the bending mode, and the dislocation mode is ignored. The Timoshenko beam theory as proposed by Timoshenko [22,23], which allows both bending and shearing deformations of beam, is perhaps a suitable beam model for simulate the tunnel longitudinal behaviours subjected to excavations. The deformation characteristics of Timoshenko beam are illustrated in Fig. 1b. The