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Simplified method for evaluating shield tunnel deformation due to adjacent excavation

Rongzhu Liang[a,b,*], Wenbing Wu[a], Feng Yu[c], Guosheng Jiang[a], Junwei Liu[b]

[a] Engineering Faculty, China University of Geosciences (Wuhan), Wuhan, Hubei 430074, China
[b] Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, China
[c] School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou 310018, China

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ABSTRACT

Due to the repaid development of underground space in big cities, increasing excavation pits is being constructed or planned in a close proximity to existing metro tunnels in dense urban areas. Adjacent excavation inevitably changes ground stress state and leads to soil movements around nearby tunnels, which may cause a series of adverse impacts on the underlying existing tunnels. Thus, to evaluate the responses of existing shield tunnels associated with adjacent excavation tunnel is crucial and essential for geotechnical engineers. Current semi-analytical methods generally utilize the Winkler foundation with the Vesic's subgrade modulus to consider tunnel-excavation interactions. However, the Winkler model cannot further consider the interaction between adjacent springs and the Vesic's subgrade modulus expression is incapable of considering the effect of tunnel embedment depth on the tunnel-ground relative stiffness. In this paper, a simplified analytical method is thus proposed to predict the shield tunnel behaviors associated with adjacent excavation by introducing the Pasternak foundation model with a modified subgrade modulus. The shield tunnel is treated as a continuous Euler-Bernoulli beam resting on the Pasternak foundation model and a modified subgrade modulus expression is presented to consider the effect tunnel embedment depth on subgrade modulus. Two-stage analysis method is applied to analyze the tunnel responses. First, the excavation induced vertical unloading stress acting on the underlying tunnel is calculated via widely-used Mindlin's solution, ignoring the presence of the existing shield tunnel. Second, the responses of the shield tunnel due to the imposing vertical unloading stress are analyzed using the finite difference method. The feasibility of the proposed method is verified by comparison with the results from a three-dimensional finite element analysis and two published filed measurements. The predicted results are also compared with the results from the Winkler-based method. Finally, parametric studies are performed to investigate the effects of different factors on the responses of existing shield tunnel, including the ground elastic modulus, excavation depth and excavation geometry.

1. Introduction

In congested urban cities, metro system plays an extremely important role in city traffic systems and everyday thousands of people travel by metro trains. The safety and serviceability of existing metro tunnels are always under serious concern. Due to the rapid development of underground space in big cities, it is an increasing commercial demand for construction of car parks or underground supermarkets in a close proximity to metro tunnel lines. The adjacent geotechnical engineering activities, such as deep excavation, may cause adverse impacts on or even potential damage to the nearby shield exiting tunnels. If the induced tunnel deformation and internal forces exceed the capacity of tunnel structures, segment cracking, leakage and even longitudinal distortion of railway track may likely occur subsequently, which may seriously threaten the smoothness and safety of running trains. Chang et al.(2001) extensively reported a shield tunnel damage case history due to an adjacent deep excavation. Cracks in segmental linings and distortion of connected blots were observed in this case history. Therefore, it is one of major challenges for city designers and geotechnical engineers to evaluate shield tunnel responses associated with an adjacent excavation. Lots of studies have been published to investigate the effects of an adjacent excavation on existing shield tunnels by means of various methods, including field monitoring (Burford, 1988; Chang et al., 2001; Simpson and Vardanega, 2014), centrifuge modelling test (Zheng et al., 2010; Ng et al., 2013; Huang et al., 2014), numerical analysis (Lo and Ramsay, 1991; Dolezalova,

* Corresponding author at: Engineering Faculty, China University of Geosciences (Wuhan), Wuhan, Hubei 430074, China.
E-mail addresses: liangcug@163.com (R. Liang), zjuwwb1126@163.com (W. Wu), pokfulam@163.com (F. Yu), jianggs65@vip.sina.com (G. Jiang), liujunwei0208@126.com (J. Liu).

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2001; Sharma et al., 2001. Hu et al., 2003; Zheng and Wei, 2008; Liu et al., 2010; Devriendt et al., 2010; Huang et al., 2013; Shi et al., 2015) and semi-analytical methods (Zhang et al., 2013a; Zhang et al., 2013b, 2015).

Compared to the high cost filed measurement and centrifuge modelling test and complex finite element model building, analytical method serves as a rapid and low cost approach to estimate the shield tunnel responses to an adjacent excavation at the design and preliminary planning stage. Yet few analytical methods have been proposed (Zhang et al., 2013a; Zhang et al., 2013b, 2015) for estimation of shield tunnel responses due to excavation. Among these previous analytical methods, a existing shield tunnel is commonly treated as a continuous beam resting on a Winkler type foundation and the subgrade modulus is always estimated using the Vesic′s expression (Vesic, 1961). The Winkler model presented by Winkler (1867) is based on the hypothesis that the soil is made up by continuously distributed, non-connected discrete springs and the pressure at any point on the surface is proportional to the ground deflection. It is expressed as

$$p = kw(x) \tag{1}$$

where p is the pressure at top of spring; k is the coefficient of subgrade modulus; and $w(x)$ is the deflection of beam.

However, this model has some shortcomings of the inherent discontinuity of adjacent springs, which cannot perfectly represent the mechanical behavior of foundation material and gives inaccurate prediction of bending moments on beams (Tanahashi, 2004). Besides, the Vesic′s expression is deduced by allowing an infinite beam resting on the ground surface (Vesic, 1961). Yu et al. (2013) and Attewell et al. (1986) both indicated that the tunnel (or pipeline)-soil relative stiffness exhibits a high sensitivity to the tunnel (or pipeline) embedment depth. In reality, shield tunnels are generally constructed in a certain depth below ground surface. Therefore, using the Vesic′s expression to estimate the tunnel-soil interaction associated with excavation may lead to misleading results.

To overcome the shortcomings of previous semi-analytical methods, a simplified analytical method is proposed to evaluate the responses of existing shield tunnels to adjacent excavation. In this proposed method, the Pasternak foundation is used to simulate tunnel-ground interaction behaviors (Pasternak, 1954). A shear layer on the top of springs is introduced to consider the continuity of adjacent springs. It is expressed as

$$p = kw(x) - G_c \frac{\partial^2 w(x)}{\partial x^2} \tag{2}$$

where G_c is the shear stiffness of the shear layer.

Moreover, a modified coefficient of subgrade modulus expression, which is capable of considering the buried depth of tunnel, is also proposed. The proposed simplified method provides a rapid, effective and low cost estimation of a shield tunnel responses induced by an adjacent excavation engineering. The validity of the proposed method is examined by a three-dimensional finite element analysis and two published filed case histories. The results obtained from the proposed method are also compared and discussed with those from the Winkler-based method. Finally, parametric analyses are also carried out to investigate the effects of various factors on the deformation and internal forces of a shield tunnel, including the ground elastic modulus, excavation depth and geometry.

2. Analysis method

Two-stage analysis method is selected and utilized in this analysis, which is widely used in structure-ground interaction problems (Zhang et al., 2013a; Zhang et al., 2013b; Zhang and Huang, 2014; Zhang et al., 2015; Yu et al., 2013). According to the two-stage analysis method, the excavation-tunnel interaction analysis is mainly divided into two individual but connected stages. First, the excavation induced vertical unloading stress acting on the underlying tunnel is calculated by Mindlin′s Green function (Mindlin, 1936), ignoring the presence of existing shield tunnel. Second, the shield tunnel responses to the corresponding unloading stress are computed numerically using finite difference method.

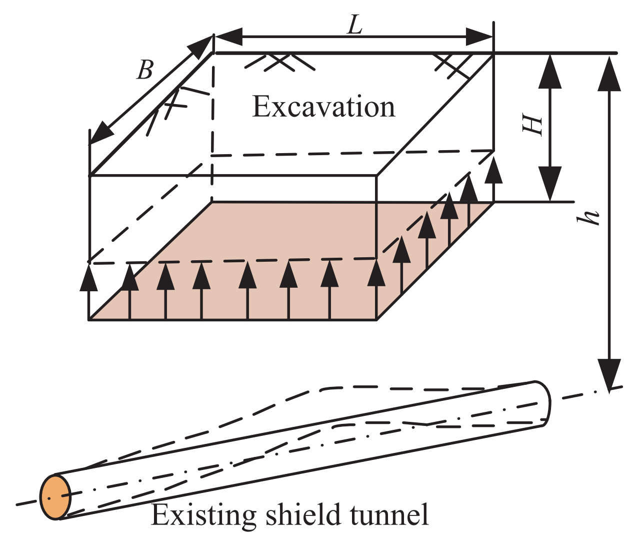

Fig. 1. Interaction between the excavation and existing shield tunnel.

2.1. The unloading stress caused by the adjacent excavation

Fig. 1 shows that a rectangular basement is excavated above a existing shield tunnel. Fig. 2 shows the general relative position between the excavation and the existing shield tunnel. As shown in Fig. 1, the length, width and depth of the excavation are denoted by L, B and H, respectively. The centerline of underlying the existing shield tunnel is buried at the depth of h below the ground surface. The unloading stress imposing on the shield tunnel can be obtained using the Mindlin′s formula (Mindlin, 1936), ignoring the effects of the presence of the existing tunnel.

Based on the Mindlin′s formula, the unloading vertical stress $q(x)$ along the existing tunnel at the tunnel centerline level is obtained:

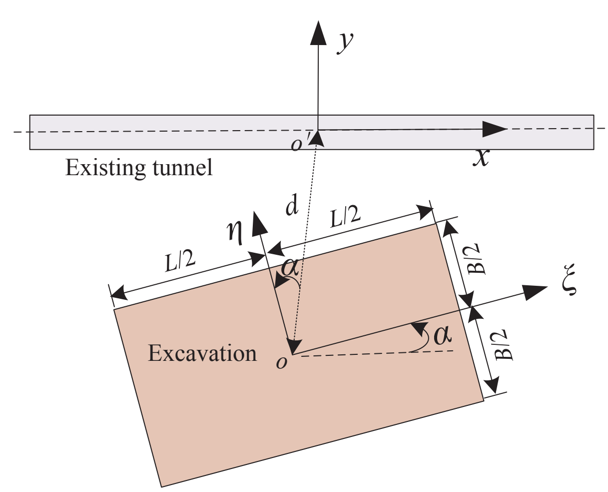

Fig. 2. Plan view of the relative position between existing tunnel and excavation.