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Mechanical responses of existing tunnel due to new tunnelling below without clearance

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ABSTRACT

With the development of urban subway, there are more projects of new subway construction below existing subway. The project is more challenging if the new subway is excavated below the existing subway with no pillar in between. In this research, we propose an analytical solution to investigate the mechanical responses of the existing tunnel due to new tunnel construction below without clearance. We put forward a superposition method based on the Winkler model to simulate the absence of the springs under the existing tunnel at the intersection of the new and existing tunnel. The proposed solution is successfully validated by FEM simulation. The influences of the input parameters of the model, including the range of deleted springs, the coefficient of subgrade reaction, and the equivalent bending stiffness, on the deflection and the bending moment of the existing tunnel, are studied. The research can serve as a reference to ensure both the safety and the serviceability of existing tunnels in case of new tunnelling below existing tunnel without clearance.

1. Introduction

As more subway lines are built in urban underground areas, the case that a new subway tunnel constructed below an existing tunnel is more frequently encountered. The serviceability of the existing tunnel needs to be ensured both during and after the construction of the new tunnel. However, due to the inherent complexities of the interactions between tunnel and ground, it brings great challenges to researchers and engineers to study the mechanical behaviours associated with new tunnel construction below the existing tunnel.

Field measurements of such adjacent tunnelling projects provide both valuable information for future design and an important reference for numerical model validation. The cases of new tunnel construction below the existing tunnel, although rare, have been reported by some researchers (Table 1). The existing tunnel can be supported by cast iron lining, masonry lining, composite lining, or segmental lining. And the new tunnel can be supported by composite lining, sprayed concrete lining or segmental lining. The clearance between the existing tunnel and the new tunnel varies from 0 to 9.8 m.

Numerical analyses provide a powerful tool to gain insights into different problems of underground constructions (Feng et al., 2016, Feng and Hudson, 2010; Hao et al., 2016; Zhu et al., 2014). The state of art, and the development trend in numerical modeling have been summarized by Jing and Hudson (2002). In addition, A series of two-dimensional (Addenbrooke and Potts, 2001; Chehade and Shahrour, 2008) and three-dimensional (Chakeri et al., 2011; Do et al., 2014; Avgerinos et al., 2017) numerical simulations have been adopted to investigate the site-specific cases of new tunnel construction below the existing tunnel. Attentions are mainly focused on the mechanical responses of the existing tunnel.

Physical model tests are also used to investigate the interactions due to new tunnel construction below the existing tunnel. Both 1 g laboratory tests (Kim et al., 1998) and centrifuge tests (Ng et al., 2013, 2016; Boonyarak and Ng, 2016) have been carried out. Different geotechnical and geometric conditions have been considered and the excavation process has been appropriately modelled.

Analytical methods present a simple and effective way to investigate the responses of the existing tunnel due to adjacent new tunnel excavation. The present analytical research concentrates on the problems of new tunnel construction above the existing tunnel by using the theory of beam on elastic foundation (Zhang et al., 2013a, 2013b; Liang et al., 2016, 2017). The existing tunnel is simplified as a beam resting on elastic foundation. The beam can be modelled as either a Euler-Bernoulli beam or a Timoshenko beam. The elastic foundation model can be either the Winkler model or the Pasternak model. The additional pressure induced by new tunnel excavation on the existing tunnel is calculated by Mindlin's solution (Mindlin, 1936).

Recently, a case of new tunnel construction below the existing tunnel with zero clearance in London has been reported by Gue et al. (2017). Similar projects of new tunnel construction below the existing

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Table 1
Cases of new excavation below existing tunnel.

City	Support of new tunnel	Support of existing tunnel	Pillar thickness (m)	Skew angle (°)	Reference
London	Precast concrete segments	Spheroidal Graphite Iron	2	90°	Kimmance et al. (1996)
London	Precast concrete segments	Cast-iron segments	5.6–9.8	90°	Standing and Selman (2001)
London	Sprayed concrete lining	Concrete segments	7	69°	Cooper et al. (2002)
London	Concrete segments	Masonry lining	3.6	21°	Mohamad et al. (2010)
Shenzhen	Concrete segments	Composite lining	1.78; 2.76	55°	Li and Yuan (2012)
Beijing	Composite lining	Concrete segments	2.6	90°	Fang et al. (2015)
London	Sprayed concrete lining	Cast-iron segments	0	75°	Gue et al. (2017)

tunnel without clearance have also been built in Beijing subway (Tao et al., 2013; Zhang et al., 2017). In these cases, the existing tunnel can be either horseshoe or rectangular shape, and the shape of the new tunnel is mostly rectangular. To facilitate the design process of such problem, a simple analytical solution is required to calculate the mechanical responses of the existing tunnel. As the coefficient of subgrade reaction of the existing tunnel at the intersection of the existing and new tunnels is zero when the bottom of the existing tunnel is exposed during new tunnel construction below, the present analytical solutions are unavailable to solve the concerned problem. To address this issue, in this research, we aim to propose a simple analytical solution to calculate the effects of the existing tunnel due to new tunnel construction below without clearance using the theory of beam on elastic foundation. A superposition method is adopted to analyse the final deflection of the existing tunnel. The results obtained by the proposed analytical solution agree well with the numerical simulation results. Parametric analyses are performed to study the influences of different factors on the mechanical responses of the existing tunnel. The proposed analytical solution can serve as an effective way to study the mechanical responses of the existing tunnel due to new tunnel excavation below without clearance.

2. Analytical solution

2.1. Soil-tunnel interaction model

The objective of this research is to study the mechanical responses of the existing tunnel due to new tunnel construction below with zero clearance in between. A typical geometry of the problem is shown in Fig. 1. The theory of beam on elastic foundation is adopted for calculation, which is suitable and simple for analysing the global behaviour of the concerned beam structure. The calculation model of the problem is shown in Fig. 2. The existing tunnel is simplified as a continuous Euler-Bernoulli beam resting on Winkler foundation, which consists of closely spaced independent linear springs to represent the soil-structure interaction. As the soil below the existing tunnel at the intersection of the new and existing tunnels is excavated, the springs at the intersection are deliberately deleted. The additional pressure $q(x)$ acting on the existing tunnel is produced by the unloading load p associated with the new tunnel construction, which can be calculated by elastic solutions.

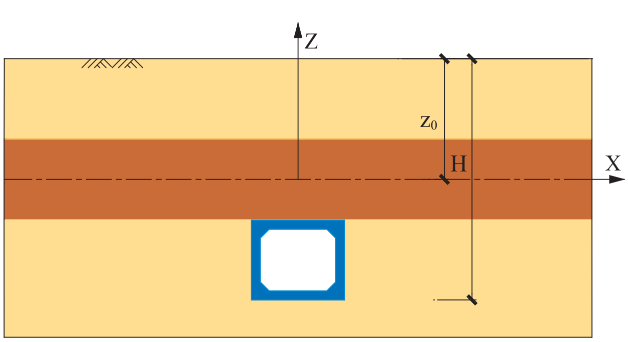

Fig. 1. New tunnelling below existing tunnel without clearance in between.

2.2. Solution method

According to the theory of beam on elastic foundation, the governing equation for an infinitely uniform beam on Winkler foundation is:

$$E_bI\frac{d^4W(x)}{dx^4} + KBW(x) = q(x)B \tag{1}$$

where E_bI is the equivalent bending stiffness of the beam; B is the cross-sectional width of the beam; K is the coefficient of subgrade reaction; $q(x)$ is the additional pressure acting on the beam caused by new tunnel construction; and $W(x)$ is the additional deflection of the beam associated with new tunnel construction.

The solution of the governing equation can be written as:

$$W(x) = W_0(x) + v(x) \tag{2}$$

where $W_0(x)$ is the general solution of Eq. (1), and $v(x)$ is the particular solution related to $q(x)$.

The general solution can be written as:

$$W_0(x) = e^{\beta x}(C_1 cos\beta x + C_2 sin\beta x) + e^{-\beta x}(C_3 cos\beta x + C_4 \sin\beta x) \tag{3}$$

where the characteristic of the system $\beta = \sqrt[4]{KB/4E_bI}$. The parameters C_1, C_2, C_3, and C_4 are four constants of integration, which can be determined by boundary conditions.

Since $W(x) = 0$ at $x \to \infty$, Eq. (3) can be simplified as:

$$W_0(x) = e^{-\beta x}(C_3 cos\beta x + C_4 \sin\beta x) \tag{4}$$

If a concentrated load P is applied at the origin of the infinite beam (Fig. 3(a)), the rotation angle $\theta(x)$ and the shear force $Q(x)$ can be obtained by Beam Theory:

$$\begin{cases} \theta(x) = \frac{dW_P(x)}{dx}\Big|_{x=0} = 0 \\ Q(x) = -E_bI\frac{d^3W_P(x)}{dx^3}\Big|_{x=0} = -\frac{P}{2} \end{cases} \tag{5}$$

By substituting Eq. (4) into Eq. (5), the constants C_3 and C_4 are:

$$C_3 = C_4 = \frac{P\beta}{2KB} \tag{6}$$

The vertical deflection of the infinite beam caused by a concentrated load P at the origin can be expressed as:

$$W_P(x) = \frac{P\beta}{2KB}e^{-\beta x}(cos\beta x + \sin\beta x) \tag{7}$$

When the infinite beam caused by a load $q(\delta)$ acting on an infinitesimal element length $d\delta$ at an arbitrary position δ (Fig. 3 (b)), the origin of the infinite beam can be assumed to shift from O to O_1. The resultant deflection $dW(x)$ can be calculated by using Eq. (7), in which P is substituted with $q(\delta)Bd\delta$ and x is substituted with $|x-\delta|$, respectively. That is:

$$dW(x) = \frac{q(\delta)d\delta\beta}{2K}e^{-\beta|x-\delta|}(cos\beta\,|x-\delta| + \sin\beta\,|x-\delta|) \tag{8}$$

The general deflection $W(x)$ of the infinite beam caused by additional distributed pressure can be obtained through integrating Eq. (8):