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Comparative study of construction methods for deep excavations above shield tunnels

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ABSTRACT

Although an appropriate construction method contributes to minimizing the excavation-induced impact on existing facilities, few studies have focused on the comparison and optimization of the construction methods for engineering projects in practice. In this paper, Three-dimensional (3D) numerical simulations are carried out to compare the construction methods for an excavation above shield tunnels through a case history, which has been constructed by a novel excavation method, referred to as divided alternate excavation method (DAEM). A 3D numerical model is developed in the finite element (FE) software, ABAQUS 6.10, to simulate the practical construction process of the DAEM, and the numerical results are analyzed in combination with the field data. Comparative studies are performed by simulating the hypothetical construction schemes of two conventional excavation methods that were proposed for the investigated case. Numerical results confirm the effectiveness of the DAEM on controlling the excavation-induced underlying tunnel deformation. Extensive parametric studies of the DAEM are performed for further investigation. Through the comparative studies and parametric studies, suggestions are proposed for optimization of construction methods for deep excavations above shield tunnels.

1. Introduction

Shanghai has experienced unprecedented infrastructure construction activities in the past decades. To relive the traffic pressure in this congested urban area, many metro tunnels have been excavated in this period using earth pressure balanced (EPB) shield machines. Meanwhile, more and more highway tunnels are being constructed, which calls for deep excavations supported by retaining structures. Deep excavations will cause potential large soil deformations inside and outside of the excavation pit, and will result in serious influence on adjacent existing shield tunnels (Chai et al., 2014; Son and Cording, 2005). If excessive stress and deformation are induced in the shield tunnels, cracks will be developed and these tunnels may be damaged (Chang et al., 2001). Therefore, to minimize the adverse impact, it is of particular importance to compare and optimize the schemes before construction.

Tunnel deformations resulted from an adjacent deep excavation are a common problem encountered by engineers (Cooper et al., 2002; Lu and Hanyga, 2005a; Tan et al., 2015; Chen et al., 2016; Li et al., 2017a,b; Zhang et al., 2017). Chang et al. (2001) reported a case history in which a section of a tunnel was damaged as a result of an adjacent excavation. To keep the existing tunnels from damaging, several remedial measures or countermeasures are adopted, including soil reinforcement within excavation area (Hu et al., 2003; Huang et al., 2006; Chen et al., 2013) and stiffness enhancement of retaining structures (Huang et al., 2013). Moreover, a rational excavation sequence also helps to control the deformation of the existing tunnels efficiently by following the time-space effect (Hu et al., 2003; Lu and Hanyga, 2005b; Liu et al., 2011; Li et al., 2014). However, the effectiveness of these remedial measures or countermeasures on the tunnel deformation needs to be evaluated.

Numerical method is a feasible tool and has been widely used to evaluate the response of tunnels to adjacent deep excavations (Zhang et al., 2013; Ng et al., 2013, 2015a, 2015b). Two dimensional (2D) numerical simulation is preferred because of its high computational efficiency (Chen et al., 2011; Sharma et al., 2001). Using the 2D FEM, Hu et al. (2003) predicted the vertical and horizontal displacements of two adjacent tunnels induced by the excavation. Dolezalova (2001) predicted the deformation and stress change in a tunnel induced by an open excavation, and the computed results agreed well with the monitoring data. Zheng and Wei (2008) studied the response of existing tunnels at three typical locations to the excavation, namely at the central line under the excavation bottom, directly under the base of the diaphragm wall and outside of the diaphragm wall. Considering the

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asymmetric nature between the excavation and the adjacent tunnels, three dimensional (3D) numerical simulations are needed to achieve more accurate estimations. Through 3D simulations, Liu et al. (2011) analyzed various influence factors, such as the ground reinforcement depth, the excavation sequence and the skew angle between the new tunnel and the existing tunnels, on the deformation of underlying tunnels. More recently, Huang et al. (2013) studied parameters that may affect the tunnel response, including the relative position of the tunnel with respect to the excavation, tunnel diameter, excavation dimensions, and tunnel protection measures. Until now, many numerical simulations have been carried out to simulate the excavation process and the structural response of the adjacent tunnels. However, only few focused on quantifying the effect of construction methods on the deformation of tunnels, although an appropriate construction method plays an important role in practice (Ferrada and Serpell, 2014; Zhang et al., 2016).

In this paper, 3D numerical simulations are performed to compare three construction methods through a case history of a deep excavation located above metro tunnels. The effect of the construction method on the excavation-induced underlying metro tunnel deformation is discussed and quantified. Moreover, extensive parametric studies are conducted to optimize the novel construction method of DAEM.

2. Overview of the case

The investigated case was an excavation of a highway tunnel located above an existing metro tunnel in Shanghai. The highway tunnel was constructed by the cut-and-cover method. The excavation of the highway tunnel was 27.1 m in width and 11.5 m in depth, and the crossing length over the metro tunnel is 150 m. The underlying metro lines were composed of two shield tunnels, i.e. the inbound and the outbound, which were excavated using earth pressure balanced (EPB) shield machines. The internal diameter and the thickness of the lining structure of the tunnels were 6.2 m and 0.35 m, respectively. More detailed information of the project was reported by Chen et al. (2015).

Metro tunnels are the lifelines of a city and are sensitive to adjacent constructions. To safeguard the safety of these lifelines, strict guidelines have been made for deep excavations adjacent to metro tunnels, e.g. the construction-induced maximum vertical displacement of the tunnels must be controlled within 20 mm (SZ-08-2000 Shanghai Municipal Engineering Authority, 2000). In this project, the clearance between the new highway tunnel and the existing tunnels' crown was only 4 m, so appropriate countermeasures were needed before and during construction. Soil improvement is an efficient way to reduce the rebound of soil below the excavation surface (Wang et al., 2010). The deep soil mixing (DSM) method was used in this project to improve the surrounding soil (Chen et al., 2013) and the tunnels were uplifted with a maximum value of 3.7 mm during the soil improvement process. Therefore, the heave of the underlying metro tunnels caused by the excavation must be controlled within 16.3 mm.

To safeguard the metro tunnel, Chen et al. (2015) proposed a novel construction method of a divided alternate excavation method (DAEM) for the project by following the time-space effect. Fig. 1 illustrates the principle and concept of the DAEM by comparing to the slope excavation and the divided successive excavation. In the slope excavation as shown in Fig. 1(a), the influence of unloading and the unloading width is increased compared with a vertical-sided excavation method. This will increase the uplift of the underlying tunnels during a single excavation. In the divided successive excavation, the soil in the excavation is removed from one side to the other side in turn, so the construction duration is long and the superimposed effect is significant as shown in Fig. 1(b). To overcome the disadvantages of conventional excavation methods and to better utilize the principle of the time-space effect and stiffness of tunnel, the DAEM was proposed to decrease deformation of the metro tunnel and to shorten the construction time as shown in Fig. 1(c). In this construction method, isolated piles and resistance piles are installed on the both sides of the tunnels. Dividing walls are also constructed to divide the big excavation into small pits so that a single unloading volume and lateral earth pressure can be reduced (Wang et al., 2003; Chen et al., 2017; Li et al., 2017a,b). 24 dividing walls are constructed before excavation with the spacing from 6 to 8 m, as shown in Fig. 2. These small pits are grouped and the pits in a group are excavated simultaneously in each construction stages. Three level struts are designed to support the retaining walls in each small pit, and soil above the third level strut is excavated in layers, leaving the last layer of soil with a thickness of 3–4 m. The corresponding struts should be installed timely after each layer of soil is excavated. In order to minimize the tunnel deformations, the last layer of soil is excavated in blocks. After the construction of base slabs is completed, the next construction stage can be carried out. The novel construction method of DAEM was successfully applied in the project. Although the deformation of the underlying metro tunnels was controlled within the allowable value, the efficiency of this construction method needs to be evaluated.

3. Numerical simulation

Numerical simulation is a feasible method to model the construction process and capture the structural response of the metro tunnels to adjacent excavations. In this section, the finite element (FE) software, ABAQUS 6.10, is used to evaluate the deformation of the underlying metro tunnel due to soil unloading in the highway tunnel excavation with the construction method of DAEM.

3.1. Numerical model

Considering the skew angle between the highway tunnel and existing tunnels, it is necessary to model all existing tunnels in three-dimensional (3D) conditions. To eliminate the influence of boundary conditions on numerical results, the dimensions of the model are set to 328 m in length, 150 m in width and 60 m in depth, as shown in Fig. 3. As for boundary conditions, the horizontal movements of nodes on the four side boundaries are restrained with vertical movement allowed. All nodes at the bottom of the model are fixed.

The model consists of subsoil layers, retaining structures, struts, slabs and tunnel linings. The soil mass is modeled by a total of 133,040 solid elements. The tunnel linings, slabs and retaining structures are modeled as shell elements, and the struts are simulated using beam elements. The structural model of the deep excavation and the underlying metro tunnels is presented in Fig. 4. 16,127 shell elements are used for modeling the tunnel linings, slabs and retaining structures. The struts are modeled by 1700 beam structural elements.

3.2. Input parameters

The concrete structure units of both the shell elements and beam elements were modeled as an isotropic linear elastic material with a Poisson's ratio of 0.15. Considering stiffness reduction due to cracks in the concrete, the stiffness of retaining walls, protecting walls, dividing walls and struts is reduced by 20% (Lim et al., 2010) from the nominal value with an input Young's modulus of 24 GPa. To consider the influence of joint on the stiffness, the effective rigidity ratios of the lining for circumferential and longitudinal direction are set to be 0.7 and 0.17 as suggested by Huang et al. (2013) and Chen et al. (2016). Thus the input Young's moduli in circumferential direction and longitudinal direction for lining are 21 GPa and 5.1 GPa, respectively. For modeling soil behavior in excavation, Hardening-Soil Model (HS) is now becoming prevalent among users of FEM analysis for its competence in considering stress history of soils. Nevertheless, it still has difficulties in defining reasonable model parameters due to lack of laboratory and field tests. A fairly simple model with credible physical parameters is preferred (Liao et al., 2013; Ou et al., 2013; Hsieh et al., 2013). The