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Analysis of ground movement due to metro station driven with enlarging shield tunnels under building and its parameter sensitivity analysis

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ABSTRACT

Using expanding excavation based on shield tunnel can be regarded as a new approach to construct a metro station, especially when traditional methods cannot be implemented. This paper focuses on the ground movement property caused by shield tunneling and expanding construction. Ground movement property and construction influence scope, which happens during the construction process, are obtained by large numbers of numerical calculations and monitoring measurements. Results show that expanding excavation is the main factor which affects ground movement, and its influence will increase as the stability of surrounding rock deteriorates. Besides, horizontal displacement and vertical displacement (uneven settlement) are the two important factors which lead to building deformation and cracks; therefore, more attention should be given to these areas where the maximum displacement may occur during the construction process. Analysis of the two parameters, length to diameter ratio and depth to diameter ratio, indicates their relationship with safety of tunnel and building. Influence degree and scope of ground settlement are obtained due to change of the two parameters. The practical importance of this analysis is that we can judge whether building and tunnel are in a dangerous zone and thereby adopt relevant pre-reinforcements to ensure their safety. Later with the comparison of numerical simulation and *in-situ* data, we verify the accuracy of simulation.

1. Introduction

At present, when building a metro station, conventional processes and technologies cannot be implemented smoothly because of restrictions caused by surrounding environment (e.g., launching and receiving shafts cannot be constructed on the line because of the existence of buildings and underground utilities). However, these problems can be effectively solved when the shield tunneling method or the expanding shield tunnels method are utilized to construct a metro station directly. Meanwhile, construction period can be shortened significantly and construction quality will also be improved, which will definitely bring practical and economic significance (Lu, 2007; Li, 2007; Liu, 2010). Both shield tunneling and expanding construction will induce disturbance to the surrounding rock and cause ground movement; however, what exactly the two processes "contribute" to the ground movement is still unknown; besides, considering the existence of a building, when H/D and L/D change (H is the depth of tunnel, L is the horizontal distance between tunnel and building, D is diameter of shield tunnel), the influence of two construction processes on stratum movement is also unknown. Currently, some published papers, which are related to this subject, are mostly about construction schemes. For example, Nakamura et al. (2003) introduced a method to excavate a rectangular cross-section for the Kyoto Municipal Subway. Shirai et al. (2005) reported a new technology, namely using the large-diameter curved pipe roof construction method to construct large underground spaces. Kunihiko and Kenichi et al. (2006) presented that a large diameter shield tunnel was used for the construction of subway, and he also described a non-cut-and-cover method which was used for cutting the ground between two large-diameter shield tunnels. Hiroshi et al. (2006) showed that shield tunneling is utilized to build the Central Circular Shinjuku Route of Tokyo Metropolitan Expressway, and the space enlargement method was adopted to construct branch connections and ramps. Hiroshi (2007) described an Open-Cut Method which was used for the construction of enlarging road shield tunnel. However, there is little research about the effect of this construction method on the ground movement property are few. This paper presents a detailed research on such problems, with the background of a left line platform tunnel of Dongshankou metro station Guangzhou metro line 6 in China.

2. Engineering situation

The use of expanding excavation based on shield tunnels is adopted in an under-construction left line platform tunnel of

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Dongshankou metro station Guangzhou metro line 6, China. The distance from the tunnel vault to the ground surface is 18.800–19.845 m, and the distance between invert and ground is 27.045–27.534 m. The left line of station crosses a six storied building of the Second Light Industry Group. The terrane through which the left line platform tunnel passes consists mainly of moderately weathered zones and silky weathered zones. The top of tunnel crosses mainly through strong weathered zones, and it goes partly through fully weathered zones. The formation parameter and the geological section map are shown in Table 1 and Fig. 1, respectively.

3. Model building

According to the construction scheme and geological data, $FLAC^{3D}$ is used to build a three-dimensional model. Model dimension is 98 m × 50 m × 35 m, number of grid cells are 89,000, see Fig. 2. When modeling, shell element and cable element are used to simulate primary lining and rock bolts; besides we adopt beam element to simulate columns and beams. The live load of every floor is according to the code for design of building foundation (The National Standards Compilation Group of People's Republic of China, 2002). Live load of top floor is 0.5 kN/m^2, and the averaged live load of other floors is 2.25 kN/m^2. Considering the gravity of wall which transmits to the framework of the beam, the applied load to each floor is 4.9 kN/m^2.

The following assumptions are used when simulating: (1) Ground surface and each soil layer represent in homogeneous and horizontal layered distribution; (2) Groundwater seepage is overlooked, and deformation of soil itself has no relation with time; (3) Soil is isotropic and elastic-perfectly plastic material, which complies with Yield Criterion of Mohr–Coulomb; (4) We adopt deformation compatibility to calculate deformation of buildings and foundation, as well as foundation and soil.

4. Ground movement property induced by shield tunneling and expanding excavation

In urban areas, it is essential to protect pre-existing structures and underground utilities from damage due to ground movement caused by the construction of a metro station. Therefore, it is particularly important to know the influence degree and scope as a result of a metro station construction. This section will focus on this problem.

4.1. Key points displacement

In order to analyse influence degree of shield tunneling and expanding construction on the ground settlement, some points of key parts are extracted from the model, such as ground surface, distance from ground surface 1D, 2D and 3D (namely tunnel vault). We define these points as Key Points, and then we extract the vertical displacement of these points during the construction process, see Table 2. During the process of shield tunneling, it drives 1.4 m for each step, and the total steps are 25; during the process of expanding construction, it excavates 0.7 m per step, and total steps are 50. The intersection location of the building and tunnel axis is at the position of $y = 26$ m (longitudinal); therefore these key points are chosen from the section of $y = 26$ m.

As presented in Table 2, shield tunneling only has a smaller effect on surface subsidence when comparing with expanding excavation. During the process of shield tunneling, surface subsidence of the sixth step, the fourteenth step, the eighteenth step and the twenty-fifth step are 1.45 mm, 3.35 mm, 3.81 mm and 4.13 mm, respectively, and all these values are less than 10 mm. However, in contrast to shield tunneling, ground settlement caused by expanding construction is larger. As shown in Table 2, in the places of surface, depth of 1D, depth of 2D and vault, the settlement caused by expanding construction accounts for 54.96%, 54.80%, 53.70%, and 50.86% of the total settlement. With the increase of depth (above the vault), ground settlement rises sharply. After expanding construction, the settlement amount of surface, depth of 1D, depth of 2D and vault are 9.17 mm, 10.11 mm, 14.47 mm, and 20.84 mm respectively. It can be seen clearly that the settlement value of vault is two times bigger than surface subsidence.

4.2. Stratum settlement trough and three-dimensional ground subsidence surface

Based on the same reason as in chapter 4.1, section of $y = 26$ m is chosen to analyse. Stratum settlement trough and three-dimensional ground subsidence are shown in Figs. 3–6.

According to settlement curves at different depths of stratum (see Figs. 4 and 5), the shape of surface settlement curves is gentler, and its distribution range is quite bigger. With the depth increasing (above the vault), the form of settlement curves become precipitous, and their distributions are narrower. In addition, ground settlement of the same cross-section is not completely symmetrical along the axis, which can be seen clearly from Figs. 4–6. The reasons for this phenomenon are likely to be skew intersection of building and tunnel axis, and on the other hand it has some relationships with formation lithology, construction methods, groundwater and other factors.

Horizontal and vertical displacements of stratum are the two most important factors which induce building deformation. By analyzing the calculation results, the maximum horizontal displacement and disturbance range to stratum, caused by shield tunneling and expending construction, are generalized in Table 3. This data can be used to predict ground movement before construction. When the maximum horizontal displacement occurs close to underground utilities and architectural pile foundation, monitoring must be strengthened and relevant Pre-reinforcement should be adopted to ensure their normal usage and safety.

4.3. Horizontal displacement of stratum

As indicated in chapter 4.1, Z-direction displacement (differential settlement) and X-direction displacement of stratum (Stretch and squeeze) may lead to building deformation and cracks, while Y-direction displacement only has smaller influence on building deformation because of its little value.

In X-direction the shape of curve represents in stretch and squeeze, and it expresses changes in wave shape (see Figs. 7–10). Because of skew intersection of building and tunnel axis, horizontal displacements of stratum are not completely symmetrical about the centerline during the construction process. Horizontal displacements relative to the tunnel axis are in the opposite direction, and the horizontal displacement caused by expanding excavation is larger than the displacement caused by shield driving. With the increase of buried depth, the curve becomes more precipitous, and during the range of 6 m from the tunnel axial, horizontal displacement of stratum increases gradually; while the distance is more than 6 m, the variation tendency is the opposite. The influence range of horizontal movement decreases as the depth of stratum increases (see Fig. 10), and the position of the maximum horizontal displacement are different in different buried depths (see Table 3). In the working-yard, ground surface cracks occur mostly at the position around 9.5 m from the tunnel axis, which coincides with the position of the maximum horizontal displacement (see Table 3).