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Zoned and staged construction of an underground complex in Shanghai soft clay

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ABSTRACT

Construction of an underground complex in congested urban areas calls for excavation of a group of foundation pits, referred to as a pit complex, which are usually surrounded by existing facilities. In such circumstances, the safety of the pit complex and facilities during the construction are of great concern. This paper presents a case of an underground complex construction in Shanghai soft clay. A pit complex composed of two deep excavations was excavated for a Comprehensive Transport Hub (CTH) and a commercial retail area and pedestrian concourse known as South Square (SS), which were connected to an operating metro station and a railway station. During the excavation, potential deformation of metro tracks and railway tracks were expected due to extensive soil unloading. To safeguard the railway and the subway, a zoned and staged construction technology was proposed, in which several temporary partition walls were constructed in addition to necessary supporting structures, to allow the large-scale deep excavations to be divided into several independent small-scale excavations. This paper discusses the rational construction sequence of these excavations as well as reinforcement measures in detail. The construction technology was examined by extensive field data. It is found that the maximum horizontal displacement of diaphragm walls ranged between 0.05% H_e and 0.4% H_e, where H_e is the excavation depth. The vertical displacements of the railway tracks were well controlled, whereas the metro tracks heaved significantly due to unloading effect.

1. Introduction

Development of underground complexes has contributed considerably to rapid urbanization over the past two decades. An underground complex is a multifunctional underground structure in which the subcomponents are connected with each other in a complicated way. The construction of an underground complex calls for excavation of a pit complex, which is composed of a group of foundation pits. Generally, an underground complex is expected to be planned as part of the whole development of an area. However, many underground complexes must be built in different stages due to a lack of effective prediction on future requirements, or due to a motivation of decision-makers to rush (O'Reilly, 1973; Liao et al., 2013). Consequently, deep excavations conducted in later construction stages are usually connected to newly-built facilities, which may result in work facing conflict between the deep excavations and facilities in service. In such circumstances, resolving the conflict and guaranteeing the safety of the deep excavations and the facilities are the main concerns during the construction of an underground complex.

Much research in recent years has focused on the performance of deep excavation based on case histories (Clough and Reed, 1984; Ou et al., 1993, 1998; Blackburn and Finno, 2007; Osouli et al., 2010; Liu et al., 2011; Tan and Li, 2011; Tan and Wei, 2012a, 2012b; Tan and Wang, 2013a, 2013b; Shi et al., 2015; Finno et al., 2015; Mu and Huang, 2016; Rotisciani et al., 2016) and databases (Long, 2001; Moormann, 2004; Liu et al., 2005; Wang et al., 2010). Moreover, excavation-induced impact on adjacent facilities, e.g. tunnel movement (Doležalová, 2001; Hu et al., 2003; Ng et al., 2013; Zhang et al., 2013a, 2013b; Chen et al., 2016), building settlement (Ou et al., 2000; Finno and Bryson, 2002; Finno et al., 2005; Son and Cording, 2008; Schuster et al., 2009; Liyanapathirana and Nishanthan, 2016), and metro stations (Tan et al., 2015a; Liao et al., 2016), have also attracted considerable research interest. However, only limited studies have focused on construction technology and construction management in deep excavations, although it is of great importance to ensure the safety of the excavation and to minimize any excavation-induced adverse

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impact on adjacent facilities (Tan et al., 2015a). By dividing a large pit into several small ones for excavation (i.e., in accordance with a segmented construction procedure), excavation duration (i.e., wall exposure duration) can be shortened significantly and then rigid floor slabs can be cast as early as possible. Consequently, the time-dependent pit deformation can be restrained timely. Liu (1999) proposed this soil removal technique for deep excavation and defined the time-space effect (TSE). Tan et al. (2015b) emphasized the importance of quick excavation, prompt propping, timely casting, and segmented construction based on the construction of Shanghai metro stations. Ou et al. (2008, 2011) used buttress walls and cross walls to reduce excavation-induced movement. By taking advantage of TSE, Li et al. (2014a) presented an innovative top-down construction method with channel-type excavation for the long and narrow foundation pits, and Chen et al. (2015) developed a novel construction method to control the deformation of metro tunnels underlying a deep excavation. Previous work has also focused only on a single deep excavation. As geotechnical engineering has become more and more complicated, there is an urgent need to improve construction technology to minimize the construction risk during excavation of a pit complex.

This paper presents a case of an underground complex that involved two deep excavations at Shanghai West Railway Station. These excavations were connected to an existing metro station and a railway station. During the excavation, potential deformations of metro tracks and railway tracks were expected due to extensive soil unloading. To safeguard the railway and the subway, a zoned and staged construction technology was proposed. The rational construction sequence of these pits, as well as reinforcement measures, was described in detail. Moreover, a long-term comprehensive monitoring program was conducted and the responses of retaining structures and facilities were examined.

2. Background

2.1. Project description

The planned underground complex investigated in this paper is located at Shanghai West Railway Station, in Shanghai, China. It is composed of a comprehensive transport hub (CTH) and a commercial retail area and pedestrian concourse known as South Square (SS), as shown in Fig. 1. The CTH includes Shanghai West Railway Station and two underground metro stations for Line 11 and Line 15. Furthermore, a north-south underpass below the railway station was to be constructed to connect the two sides of the railway station, and a transfer channel built to connect the railway station and the two metro stations. The SS is located at the south side of the metro station of Line 11 and to the west of the Line 15 station. As the underground complex was planned, the Shanghai West station and the metro station of Line 11 were in service. The metro station of Line 15, the underpass, the transfer channel of the CTH and the SS were to be constructed.

The underpass was a one-floor underground structure, approximately 82 m by 160 m in plane, with an excavation depth of 9.7 m. The transfer channel was below the underpass, with a height of about 5 m. The metro station of Line 15 below the underpass was 280 m in length and 23.5 m in width. The maximum excavation depth of this metro station was 23.5 m below ground surface (BGS). The dimensions of the South Square were about 150 m by 115 m in plane, with a maximum depth of the excavation of about 13.5 m.

2.2. Ground condition

The construction site was generally flat with ground level (using the WuSong elevation system) ranging from 3.16 m to 4.18 m. Subsoil consisted of quaternary deposits, which were mainly composed of saturated clay, silt, and sand. Geotechnical investigations, including a series of laboratory tests and in situ tests, were carried out before the construction. Table 1 presents the results of the investigations. There were nine soil layers with a total depth up to 78 m in this project site, of which the fourth and the fifth soil layers were very soft saturated clay with characteristics of creep. The observed long-term groundwater table ranged from 0.5 m to 1.5 m below ground surface.

2.3. Main considerations

2.3.1. Safety of the railway line

The Shanghai-Nanjing Intercity High-speed Railway was the most heavily trafficked railway in China at the time of this project. The railway operates over 301 km of track, with a design speed of 350 km/h. Shanghai West Railway Station stretches across the CTH, with a width of about 64 m. Eight rail tracks in the railway station are located directly above the CTH. The railway station was planned to be reconstructed during the construction of the CTH without ceasing operation of the entire rail line, which resulted in a conflict between construction workplace and the operating railway. In order to perform the deep excavations, the conflict required resolution, and the railway needed to be safeguarded during excavations.

2.3.2. Safety of the metro line

Shanghai Metro Line 11 is the longest metro line in the world, with a mileage of 80.6 km. Construction of the line began on July 1, 2007, and the subway began operation on December 31, 2009. Before the metro lines came into service, deep excavations on two sides of metro station were carried out. The metro station was a two-floor underground structure with a bottom slab at 14.8 m below ground surface. The supporting structures of the CTH excavation and the SS excavation were connected to the metro station of Line 11. During excavations, a potential large heave of the metro station was expected due to the rebound of soil inside the excavation. Therefore, measures needed to be taken to control the rebound of the station.

2.3.3. Safety of deep excavations

Excavations conducted in soft clay cause potentially large displacement and deformation in supporting structures and surrounding soil. Excessive displacement and deformation result from inappropriate construction schemes (Gong and Zhang, 2012; Tan and Wei, 2012b), and asymmetric external loading (Chai et al., 2014) will lead to failures in the excavation and damage to adjacent facilities. In the investigated project, the railway station was located directly above the underpass, and the metro station of Line 15 was located below the underpass excavation. Moreover, the supporting systems of the CTH excavation and the SS excavation were connected to the permanent structures of the existing metro station. It was possible that during excavations, the deformation and displacement of the supporting systems could be affected by the dynamic train loading and asymmetric lateral earth pressure. The deformation of the excavations could be extremely complex, which significantly increase construction risk.

2.3.4. Design criteria

To ensure safety, strict guidelines were developed for deep excavations adjacent to rail tracks, e.g. the construction-induced maximum displacement of the rail tracks needed to be controlled to within 20 mm, and the curvature of the longitudinal deformation curve of rail tracks needed to be less than 1/15,000. (SZ-08-2000 Shanghai Municipal Engineering Authority, 2000).

3. Construction technology

For deep excavations in complex environment, a suitable construction technology is critical to safeguard the excavations and adjacent facilities. In the investigated project, a zoned and staged construction technology with some construction measures, e.g. soil reinforcement, a strengthening of supporting systems, and channel-type excavation (Li