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Effects of twin tunnels construction beneath existing shield-driven twin tunnels

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A B S T R A C T

This paper presents a case of closely spaced twin tunnels excavated beneath other closely spaced existing twin tunnels in Beijing, China. The existing twin tunnels were previously built by the shield method while the new twin tunnels were excavated by the shallow tunnelling method. The settlements of the existing tunnels and the ground surfaces associated with the new tunnels construction were systematically monitored. A superposition method is adopted to describe the settlement profiles of both the existing tunnels and the ground surfaces under the influence of the new twin tunnels construction below. A satisfactory match between the proposed fitting curves and the measured settlement data of both the existing tunnels and the ground surfaces is obtained. As shown in a particular monitoring cross-section, the settlement profile shapes for the existing tunnel and the ground surface are different. The settlement profile of the existing structure displays a "W" shape while the ground surface settlement profile displays a "U" shape. It is also found that due to the flexibility of the segmental lining, the ground losses obtained from the existing tunnel level and the ground surface level in the same monitoring cross-section are nearly the same.

1. Introduction

Urban underground areas are congested with infrastructures ranging from small pipelines and cables to large tunnels and foundations of high-rise buildings. With the increasing number of subways constructed in urban areas, cases of tunnelling adjacent to existing structures are common. Due to the inherent complexities of the existing structure–ground–tunnel interactions, it is very challenging to ensure both the serviceability of existing structures and the safety of new tunnels construction.

A significant amount of research has been performed to study the ground movements induced by the construction of twin tunnels or more (e.g., Addenbrooke and Potts, 2001; Chapman et al., 2003; Hunt, 2005; Ahn et al., 2006; Chapman et al., 2007; Laver, 2011; Divall et al., 2012; Garner and Coffman, 2013; Divall, 2013; Do et al., 2014; Ocak, 2014). The additional movements caused by the interaction between tunnels may result in asymmetric settlement troughs. The behaviours of existing structures induced by adjacent tunnelling have also been extensively studied, most of which focus on the influences on existing buildings (e.g., Boscardin and Cording, 1989; Burland, 1995; Boone, 1996; Burd et al., 2000; Mroueh and Shahrour, 2003; Zhang et al., 2013) or pipelines (e.g., Klar et al., 2005; Vorster et al., 2005; Fang et al., 2011; Zhang et al., 2012). Relatively speaking, there are only limited published data related to the response of existing tunnels to new tunnels construction nearby. Cooper et al. (2002) presented extensive monitoring records taken from the interior of two existing 3.8 m internal diameter tunnels during the construction of three 9.1 m external diameter running tunnels below in London clay (on the Heathrow Express). The vertical clearance between the new and existing tunnels is 7 m and there is a skew of 69° between them. Both the new and existing tunnels were constructed by using the shield method. Mohamad et al. (2010) adopted a distributed strain sensing technique to examine the performance of an approximate 8.5 m diameter old masonry tunnel during the construction of a 6.5 m external diameter tunnel beneath it. The minimum vertical clearance between the new and existing tunnels is about 3.6 m. The new and the existing tunnels were constructed using the shield method and the cut and cover method respectively. Li and Yuan (2012) presented data for the construction of two 6 m external diameter shield-driven tunnels below an existing 13.6 m high double-deck tunnel. The vertical clearances from the right tunnel and the left tunnel to the existing tunnel are about 2.76 m and 1.78 m respectively. Ng et al. (2013) investigated the response of an existing tunnel to

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the excavation of a new tunnel perpendicularly below it by using three-dimensional centrifuge tests and numerical modelling.

According to the literature, there is very limited knowledge on the response of an existing shield-driven tunnel to later tunnelling-induced disturbances. The data related to the relationship between the existing tunnel settlement and ground surface settlement are even less. In this paper, a case of two closely spaced tunnels excavated beneath two other existing closely spaced tunnels in Beijing, China is presented. The response of existing tunnels to new tunnels construction is investigated based on the monitoring data. The deformation characteristics of the existing tunnels and the ground surfaces in two monitoring cross-sections are compared respectively.

2. Project overview

A plan view and cross-sectional view of the existing and the new tunnels at the Ping'anli station in Beijing are shown in Figs. 1 and 2 respectively. The existing circular shaped twin tunnels, running north–south, are parts of the Beijing subway Line 4. They are horizontally parallel and are referred to as the "west tunnel" and the "east tunnel". The clearance between them is 9.0 m. They were driven by the earth pressure balance shield. The external and the internal radius of the precast segmental lining are 3.0 m and 2.7 m respectively. The segmental lining consists of five segments with a key segment (Fig. 3). The length of each segment is 1.2 m. The segments are rotated from ring to ring so that the joints do not line up along the longitudinal axis of the tunnel. The overburden depth of the existing tunnels is about 12.4 m.

The new horseshoe shaped twin tunnels, running east–west, are parts of the Beijing subway Line 6. The clearance between them is approximately 9.5 m, which slightly decreases from west to east. The new twin tunnels are referred to as the "north tunnel" and the "south tunnel", respectively. They were excavated by using the shallow tunnelling method. The shallow tunnelling method relying on manpower-excavation is particularly designed for shallowly-buried tunnels constructed in a densely built urban area (Fang et al., 2012). The thicknesses of the primary lining and secondary lining are 250 mm and 300 mm respectively. A waterproofing system is sandwiched between the primary and the secondary linings. The new twin tunnels were excavated perpendicularly beneath the existing twin tunnels. The vertical clearance between the new and existing tunnels is only 2.6 m. The top heading (with support core and temporary invert)-bench-invert excavation approach was adopted for the new twin tunnels excavation (Fig. 4).

A typical geological profile of the project is shown in Fig. 5. The profile reveals that the existing tunnels are located mainly in gravel, while the new tunnels are located in interbedded silty clay, silt, fine sand and gravel. Some mean values of the physical and mechanical parameters of the soils retrieved from the site investigation report are shown in Table 1.

According to the project design, a rectangular vertical shaft was first excavated. Then a horseshoe shaped cross adit with flat walls and invert was excavated horizontally from the shaft sheeting. After that, the new twin tunnels were excavated perpendicularly from the adit wall. The north tunnel was first excavated followed by the south tunnel with a certain lag. In order to safeguard the existing twin tunnels and facilitate the new twin tunnels construction, grouting into and above the new twin tunnels was performed. A total of eight grout holes, each of which about 30 m long, were drilled horizontally from the cross adit wall. The grouting was achieved through a sleeve pipe known as a tube à manchette (TAM). A grout mixture composed of ordinary Portland cement and sodium silicate was selected. The cross section and the longitudinal section of the long-span pre-grouting are shown in Fig. 6. During the new twin tunnels construction, forepolings and footing reinforcement piles were adopted as the auxiliary measures (Fig. 4).

3. Monitoring

3.1. Layout of monitoring points

During the new twin tunnels construction, the deformation of the existing tunnels and the ground surfaces were monitored. The layout of the monitoring points along the existing west tunnel and the east tunnel is shown in Fig. 7. The parenthesised texts in Fig. 7 indicate those for the east tunnel section. The first letter "W" or "E" of the monitoring point label indicates the "west tunnel" or the "east tunnel". The second letter "e" or "s" indicates

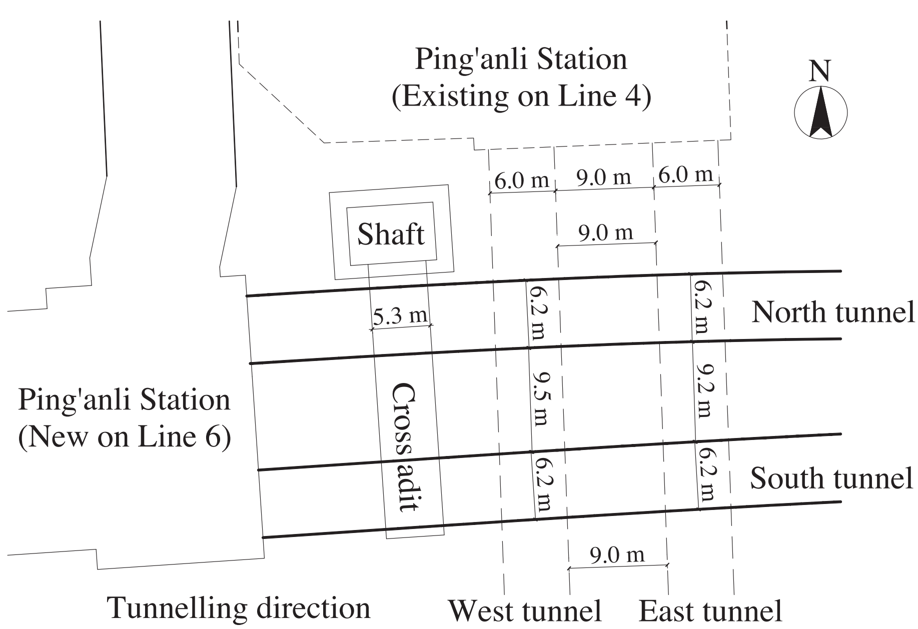

Fig. 1. Plan view at the Ping'anli station.