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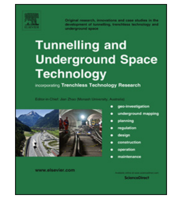

Grouting-based treatment of tunnel settlement: Practice in Shanghai

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ABSTRACT

Excessive tunnel settlement, especially differential settlement, will deteriorate the operational serviceability and safety of a metro system. This paper presents grouting-based treatment technology for tunnel settlement in the soft deposits of Shanghai, China. The aim of the grouting treatment is to control the development of the tunnel settlement. The mechanism of settlement control through grouting is presented. A dual-fluid system of cement and sodium silicate is adopted in the proposed grouting-based treatment technology. A new front-end device is designed specially to avoid blocking the grouting holes. The grouting parameters are determined based on field tests and engineering practices. Engineering cases of a double-O-tube (DOT) tunnel and twin tunnels are used to present the feasibility and efficiency of the grouting treatment. For the DOT tunnel, the grouting treatment was carried out in multiple stages; the tunnel settlement finally ceased, from an initial settlement rate of 0.4 mm/d, and the maximum horizontal differential settlement decreased from 20 mm to 10 mm. For the twin tunnels, the tunnel settlement recovered after grouting; the recovery of the maximum tunnel settlement was 8 and 11 mm for the upper- and lower-line tunnels, respectively, and the settlement finally ceased, from an initial rate of 0.027 mm/d. Moreover, *in situ* measurements of the surroundings indicate that the proposed grouting-based treatment technology creates minimal disturbance to the surrounding soil. This grouting-based treatment provides an effective way to control the settlements of tunnels in soft deposits.

1. Introduction

The city of Shanghai in China has been building metro tunnels since the 1990s. As of the end of 2016, after over 20 years of highly intense construction, there are 364 stations and 14 lines in operation with a total length of approximately 588 km. These tunnels were mainly constructed at depths of 15–33 m by the shield tunnelling method with assembled concrete segments (as shown in Fig. 1). Furthermore, most of the tunnels lie in soft deposits that have distinct rheological behaviour. The soft deposits of Shanghai are characterized by high water content (30–70%), high void ratio (1.0–2.0), high compressibility (the compression coefficient $\alpha_{0.1-0.2}$ ranges between 0.3 and 1.7 MPa^{-1}), low permeability (10^{-7}–10^{-5} mm/s) and low shear strength (the undrained shear strength is commonly lower than 20 kPa). When these soils are disturbed, their strength decreases significantly, resulting in consolidation and secondary consolidation settlement that last for a long time (Yin and Chang, 2009; Tan and Li, 2011; Tan and Wei, 2011; Yin et al., 2012; Shen et al., 2013a, b; Tan and Wang, 2013a,b).

Recent studies have revealed that tunnels built in soft deposits suffer from serious settlement during long-term operation (Ng et al., 2012, 2013; Wu et al., 2014; Shen et al., 2014; Tan et al., 2016). This may be caused by such factors as nearby construction, cyclic train loading and secondary compression of soft clay (Ng et al., 2013; Shen et al., 2014). Wang (2009) reported that the settlement of Shanghai Metro Line 2 had reached 260.07 mm, resulting in fine soil leaking into the tunnel. In May 2007, Ng et al. (2012) found a maximum tunnel settlement of 144 mm near Zhongshan Park Station of Shanghai Metro Line 2. Shen et al. (2014) reported that the average cumulative settlement of Shanghai Metro Line 1 had reached 111 mm as of the end of 2010, and that the maximum differential settlement was as high as 295 mm near the People's Square Station.

This phenomenon of long-term tunnel settlement has been reported in other similar deposits worldwide. After completion of construction, Schmidt and Grantz (1979) reported long-term settlement of the immersed Hampton Roads tunnels in southeastern Virginia, USA. The settlements of the two parallel tunnels reached 350 mm and 250 mm, respectively. It was found that the settlement of the immersed tunnels could be attributed to the underlying soil conditions and construction operations. O'Reilly et al. (1991) presented a case study of a sewer tunnel in Grimsby, UK and found that the tunnel settlement in soft soil

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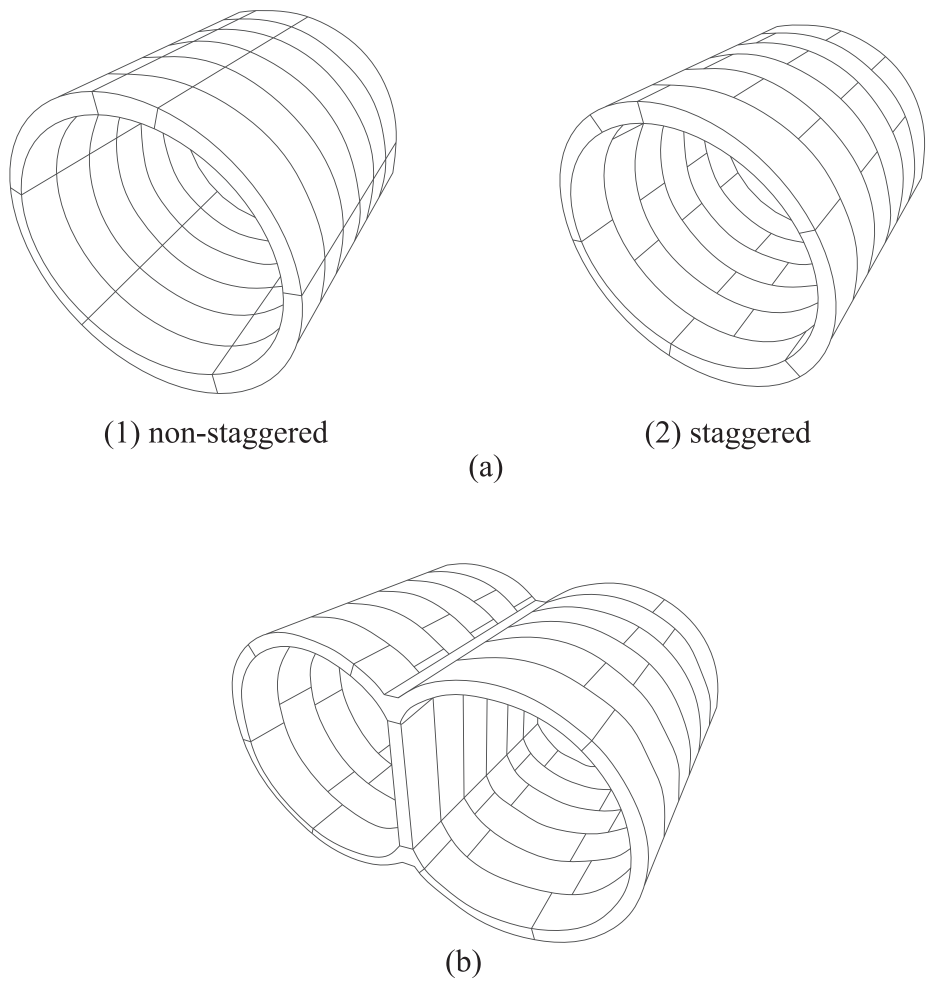

Fig. 1. Structural configuration of shield tunnels in Shanghai: (a) single-tube tunnel; (b) double-O-tube (DOT) tunnel.

lasted a long time. Grantz (2001a,b) reported on a number of rectangular immersed tunnels in several countries, all suffering from long-term settlements. Cooper et al. (2002) reported an observed settlement of more than 12 mm for the Piccadilly Line tunnel in London, UK 38 months after completion of an underneath crossing tunnel. Komiya et al. (2006) reported that the shield-driven Daiba tunnels in Tokyo, Japan suffered from excessive settlement due to soft-clay consolidation induced by construction of a nearby embankment.

Excessive differential settlement of a tunnel structure can lead to tunnel leakage, track distortion, separation between ballast bed and lining, opening of tunnel joints, additional forces, tunnel convergences and yielding of bolts (as shown in Fig. 2), all of which ultimately deteriorate the safety of tunnel operation (Doran et al., 2000; Grantz, 2001b; Cooper, 2002; Li et al., 2009; Shen et al., 2014; O'Reilly et al., 1991; Shirlaw, 1993, 1995; Zhang et al., 2018). Therefore, tunnel settlement is of great concern regarding the safety of metro operation, especially those embedded in soft soil deposits. Given the serious current situation in Shanghai and the urgent need to guarantee the safety of tunnel operations there, a way to control and treatment tunnel settlement is required urgently.

It is worth considering that compensation grouting is generally used worldwide to control ground settlement (Komiya et al., 2001; Lee, 2002). Komiya et al. (2001) investigated the effectiveness of compensation grouting at reducing surface settlement during underground construction in alluvial clay deposits in Koto-ku, Tokyo. Lee (2002) reported that compensation grouting was carried out beneath sensitive structures to prevent excessive settlement due to tunnelling for the London Docklands Light Railway Lewisham Extension (DLR-LWE) twin-tunnelling project. Ni (2010) reported on an inclined seven-story reinforced-concrete building in Taipei that was levelled using a fracture-grouting technique with quick-setting grout applied to clayey sand layers of varying thickness. Farrell (2015) reported that compensation grouting was used to mitigate tunnel-induced ground settlement in London, thus reducing the risk of damage to nearby buildings.

However, the grouting construction may disturb the surrounding soil appreciably, causing numerous negative effects especially when conducting grouting treatment on operational tunnels. In view of the deficiencies of existing compensation-grouting methods, this paper presents a grouting-based technique developed in Shanghai that involves innovative grouting equipment, parameters and technology for controlling tunnel settlement. The novel feature of this grouting-based technique is that not only can it reduce the settlement rate and even uplift the tunnel back to a safe state, it also creates minimal disturbance to the surrounding soil. It has been used successful in 50 engineering cases in Shanghai and in other soft-soil areas.

This paper is organized as follows. First, the grouting-based treatment technology for tunnel settlement is presented, including the basic principles, equipment and parameters. Then, two typical engineering cases are used to demonstrate the applicability of this newly developed technology. The first involves controlling the post-construction settlement of a double-O-tube (DOT) tunnel, while the second involves controlling the settlement of twin tunnels induced by new tunnelling underneath. Finally, we discuss differences in the effects of grouting treatment between the two cases and some key factors that influence those effects. The results indicate that this method is effective for controlling tunnel settlements in soft deposits. Moreover, the presented