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Investigation of the long-term settlement of a cut-and-cover metro tunnel in a soft deposit

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ABSTRACT

This study investigates the long-term settlement of Nanjing Metro Line 10 in China. A maximum settlement of 240 mm was measured within 5.75 years after the track system was constructed. Four settlement troughs were observed along the longitudinal direction of the railway line. The settlement of the tunnel developed rapidly in the first two years and then the rate of settlement gradually decreased. The excessive settlement and large differential settlement of the tunnel were primarily caused by the deep and non-uniform distribution of the underlying soft soil. The long-term tunnel settlement mainly consists of two components, including recompression settlement following construction and secondary consolidation settlement of the foundation. Each component of settlement was analyzed and estimated in this study. The computed results correspond well with the measured data, and the recompression deformation and the secondary consolidation deformation represents approximately 78.0–100% and 0–22.0% of the total tunnel settlement, respectively. The measured data and calculated results revealed that the lengths of the cement mixing piles used to improve the tunnel foundation are insufficient to reduce the long-term settlement. Piles entirely penetrating the soft silty clay layer are recommended.

1. Introduction

Recently, a new residential area of western Nanjing City in China has been developing in the soft floodplain area along the lower reaches of the Yangtze River. This area is in urgent need of public transportation infrastructure, such as metro lines. The 2nd and 10th metro lines are currently in service and more lines are planned in this area. However, the experience of operating lines has shown that the metro tunnels in this area are susceptible to settlement. Excessive differential settlement leads to structural cracks, leakage of groundwater and distortion of the track, which dramatically increases the maintenance cost and affects the safety of the metro system (Huang et al., 2012; Wang et al., 2014; Gong et al., 2015a). Therefore, it is necessary to investigate the mechanisms of large, long-term tunnel settlement.

Several studies have reported the tunnel settlement during construction in terms of short-term tunnel settlement (e.g., Peck, 1969; Shirlaw, 1994; Nomoto et al., 1999; Dalgic, 2002; Clayton et al., 2006; Leca and New, 2007; Almeida e Sousa et al., 2011; Zhou and Ji, 2014). But the studies on the tunnel settlement after the completion of construction in terms of long-term tunnel settlement are relatively limited. O'Reilly et al. (1991) presented a case study (covering an 11 year period) of a sewer tunnel at Grimsby in the UK and concluded that the settlement of the soft tunnel foundation took a long time to stabilize. Schmidt and Grantz (1979) analyzed the long-term settlements of the immersed Hampton Road tunnels in the USA and indicated that the settlement of the immersed tunnels corresponds well with the subsoil conditions and construction operations. Grantz (2001a, 2001b) investigated the long-term settlement of several immersed tunnels. Among several possible causes, three factors were found to be the most significant: 1) the effects of the extraction of water, gas and oil from the underlying strata; 2) poor subsoil conditions; and 3) large tidal variations. Recently, Ng et al. (2013) and Shen et al. (2014) studied the long-term settlement behavior of Lines 1 and 2 of the Shanghai Metro and revealed that the long-term settlement of the shield tunnel was mainly caused by the compression of the sandy aquifer due to groundwater pumping. Huang et al. (2015) indicated that the extent of the tunnel differential settlement is significantly affected by the variation and scale of fluctuation of soil properties. Considering the effect of the longitudinal variation of input parameters on the tunnel performance, Gong et al. (2015b) developed an improved shield tunnel design methodology by incorporating design robustness. In addition, Huang et al. (2013) and Cui and Tan (2015) analyzed the long-term differential settlement between metro tunnels and stations in Shanghai based on in-situ monitoring data. Because in situ monitoring data of long-term tunnel settlement are rare, especially for cut-and-cover

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tunnels, it is difficult to obtain sufficient information that can be applied to actual tunnel designs. Therefore, it is important to collect in situ monitoring data and identify long-term tunnel settlement mechanisms to guide the design of tunnels and to avoid large and long-term settlement of the tunnel.

This study reports and analyzes the observed settlement of a cut-and-cover tunnel of Nanjing Metro Line 10 for 5.75 years after the railway tracks were installed. Two components, including recompression settlement following construction and secondary consolidation settlement of the tunnel foundation, were estimated using different methods. By comparing the measured and calculated settlements, the mechanisms of the long-term tunnel settlement of this metro line were investigated and identified in this study.

2. Nanjing Metro Line 10

The Metro Line 10 is the main line that connects both sides of the Yangtze River in western Nanjing (Fig. 1). The line consists of 14 stations and has a total length of 21.6 km, ranging from the Yushan Road Station in the northwest to Andemen Station in the southeast. The construction of the first phase of the line (from Olympic Center Station to Xiaohang Station) was completed in February 2004, and the line has been in service since September 2005. In this study, the long-term settlement of the cut-and-cover tunnel that extends between Olympic Center Station and the entrance of the Zhongsheng Tunnel (length: 3.94 km) was investigated.

3. Geological and subsoil conditions

Western Nanjing is located on the lower reaches of the Yangtze River, where the alluvial and silty floodplain covers a large delta-shaped area. The strata in this area can be divided into five main layers and the soft subsoil is approximately 40 m thick (Xia et al., 2006). Fig. 2 shows the soil profile along the metro line from Olympic Center Station to the entrance of Zhongsheng Tunnel. The metro tunnel was mainly constructed in the soft silty clay layer with buried depth between 0 and 8 m. The thickness of the soft silty clay layer underneath the tunnel floor ranges between 0 and 27 m, which is extremely non-uniform.

The physical and mechanical properties of the subsoil layers are listed in Table 1. The representative modulus of compression of the soft silty clay is less than 3.2 MPa, and the average vertical permeability coefficient is 2.2×10^{-6} cm/s. These indexes indicate that the soft silty clay layer has a high compressibility and a low permeability. Therefore, without ground improvement, a tunnel that is constructed in this soft deposit may experience large settlements following construction and the accumulative settlement may take a long time to stabilize.

4. Methods of tunnel construction and foundation improvement

The tunnel was constructed using the cut-and-cover method. The surrounding retaining structures include drilled piles (diameter: 0.8 m) and cement mixing piles (diameter: 0.65 m) as illustrated in Fig. 3. The rectangular tunnel consists of two tubes, and each tunnel tube has a net width of 4.4 m and a net height of 5.16 m. The thicknesses of the side wall, mid-partition wall, roof and floor are 0.5, 0.3, 0.5 and 0.6 m, respectively. The concrete grade of the tunnel is C30 (unit weight: 2500 kg/m^3). Before constructing the cut-and-cover tunnel, the soft ground was improved by cement deep mixing piles (0.5 m in diameter). The pile spacing is 0.75 m. The depth of soil improvement in most sections is approximately 5 m below the tunnel floor except for the small radius curve section (distance marker: 1.112–1.570 km), where the improved depth is approximately 8 m below the tunnel floor.

5. Observed long-term settlement

5.1. Settlement of the metro line

The settlements were measured between September 2004 and June 2010. Measurements were taken at average intervals of 25 m along the railway line and at the leveling markers that were installed on the track bed (shown in Fig. 3). Fig. 4 shows the measured settlement along the metro line with time. Because the observed settlement of both tracks is very similar, only the data from the southwest-bound track are presented and analyzed in this study. The maximum settlement measured after 5.75 years is 240 mm. Four settlement troughs were observed along the line, as shown in Fig. 4. The tunnel settlements along the line were generally greater than the settlement in the underground stations. It is worth noting that the settlement measurements were initiated seven months after the completion of the tunnel construction. Thus, the actual settlement of the line can be larger than the measured data shown in Fig. 4.

Fig. 5 shows the relationship between settlement and date of observation at various locations (distance markers at 1.05 km, 2.54 km and 2.78 km). It is observed that for all three distance markers the settlement increased with elapsed time. This rate of increase is larger within the first year than the rate observed after one year, as shown in

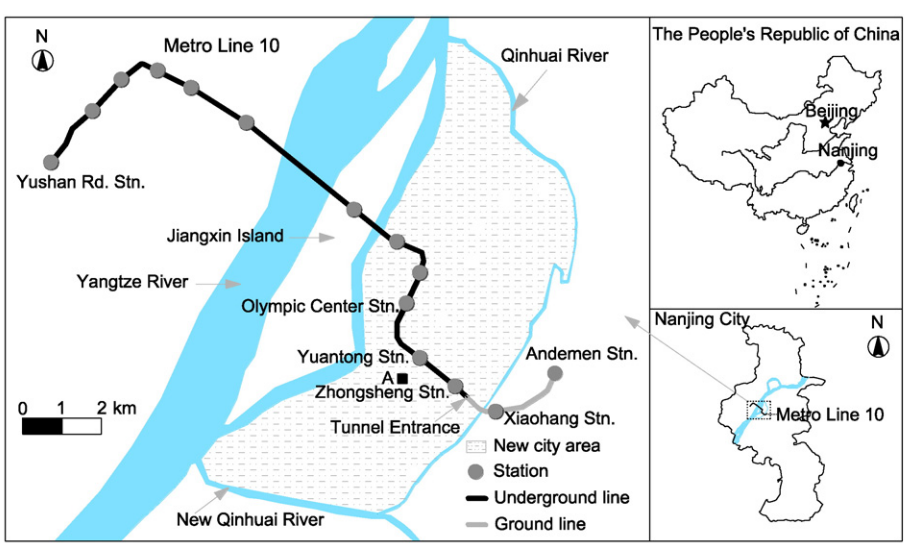

Fig. 1. Location of Nanjing Metro Line 10.