Differential Settlement and Induced Structural Damage in a Cut-and-Cover Subway Tunnel in a Soft Deposit

Shunhua Zhou[1]; Honggui Di[2]; Junhua Xiao[3]; and Peixin Wang[4]

Abstract: This study investigated the differential settlement and induced structural damage in the west extension of Nanjing Metro Line 1. The minimum and maximum cumulative settlements measured over the course of four years of operation were 1 mm and 122 mm, respectively. Four settlement troughs in the longitudinal direction of the line, as well as a periodic variation of differential settlement between the stations and the tunnel, were observed. Approximately 10% of the vertical radius of curvature of the line violates the safety limit of 15,000 m, and three typical kinds of cracks (i.e., transverse cracks in the tunnel roof and in the track bed, and inclined cracks in the outer wall) and leakage have occurred. The differential settlement of the line was mainly caused by the nonuniform distribution of underlying soft soil. The periodic variation of differential settlement between the stations and tunnel was attributed to the structural characteristics and the seasonal variation in the groundwater level. The findings presented in this paper can provide a reference for controlling the differential settlement of tunnels constructed in soft deposits. **DOI: 10.1061/(ASCE)CF.1943-5509.0000880.**

Author keywords: Cut-and-cover tunnel; Differential settlement; Structural damage.

Introduction

Long-term settlement in subway lines in the Yangtze River delta region has significantly affected the operation of these transit systems. Major tunnel settlement has occurred in lines 1 and 2 of the Shanghai Metro, and the tunnels continue to settle. In the west extension of line 1 of the Nanjing Metro, foundation reinforcement was required after construction finished because of differential settlement. Excessive differential settlement in subway structures causes excessive track deformation and exacerbates wheel-rail abrasion and vibration. Moreover, differential settlement can result in cracking and leakage in the tunnel and track structures, which not only increases maintenance costs, but also compromises safety (Huang et al. 2012). The long-term settlement of subway tunnels in this area, which has many soft soil deposits, is a problem of increasing concern because of the large number of existing subway lines in the Yangtze River delta region and the fact that additional lines are planned.

The research literature on long-term tunnel settlement is relatively limited. O'Reilly et al. (1991) reported that the settlement of the Grimsby Tunnel in the eastern United Kingdom continued for 10 years after construction before the tunnel became stable. Bowers et al. (1996) found that significant additional movement occurred in the Heathrow Express trail tunnel after construction. Schmidt and Grantz (1979) indicated that the long-term settlement of the immersed Hampton Road tunnels in Virginia in the United States was consistent with the poor condition of the underlying soil and the construction operation. Grantz (2001a, b) investigated the long-term settlement of a number of immersed tunnels. Among a variety of possible causes, three were found to be the most significant: the effects of the extraction of water, gas, and oil from the underlying strata; poor subsoil conditions; and large tidal variations. Shen et al. (2014) and Ng et al. (2013) recently studied the long-term settlement behavior of lines 1 and 2 of the Shanghai Metro and indicated that the long-term settlement of the shield tunnel was mainly caused by the compression of a sandy aquifer (Aquifer IV) below the tunnel due to groundwater pumping. Huang et al. (2013) and Cui and Tan (2015) analyzed nonuniform settlement for various subway structures in soft soil based on in situ monitoring data. However, there remains a lack of information on the long-term settlement of cut-and-cover tunnels.

This study investigated the differential settlement (measured during four years of operation) of the cut-and-cover tunnel and the induced structural damage that has occurred in the west extension of Nanjing Metro Line 1. The main causes of the differential settlement were identified by analyzing the measured settlements of the different subsoil layers and comparing the cumulative tunnel settlement with the geological conditions. The results can provide a reference for controlling the differential settlement of tunnels constructed in soft deposits.

West Extension of Nanjing Metro Line 1

Line 1 of the Nanjing Metro opened in September 2005 and was the first subway line in the city of Nanjing. The first phase (phase 1) of construction commenced in December 2000 and was completed in February 2004. Fig. 1 shows the route of Nanjing Metro Line 1. The west extension, running from Olympic Center Station (E) to Xiaohang Station (B), consists of four stations and has a total length

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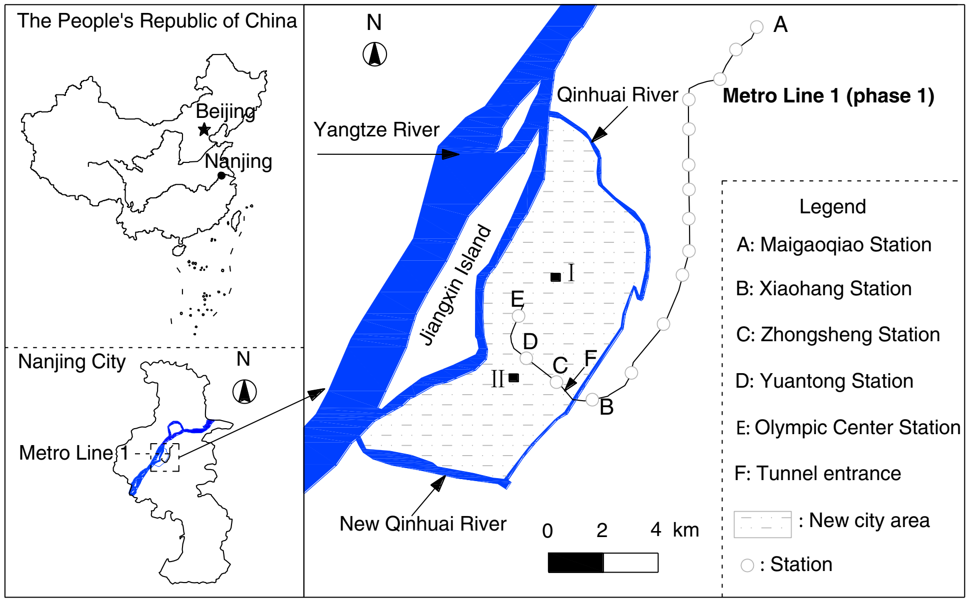

Fig. 1. Route of Nanjing Metro Line 1 (phase 1)

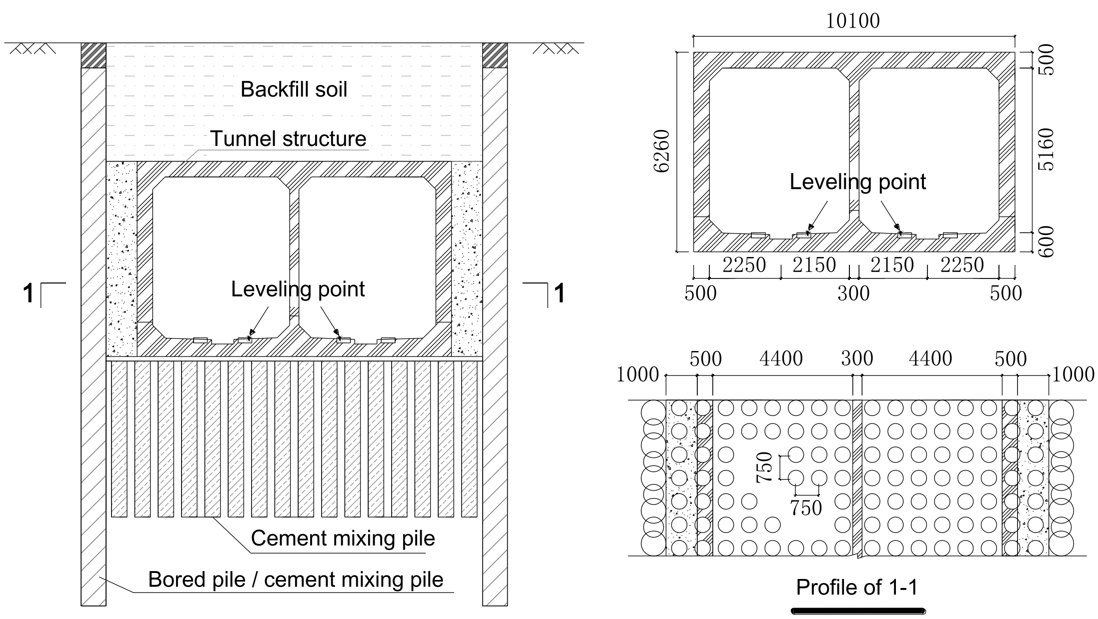

Fig. 2. Diagram of the tunnel cross section and foundation treatment (unit: millimeters)

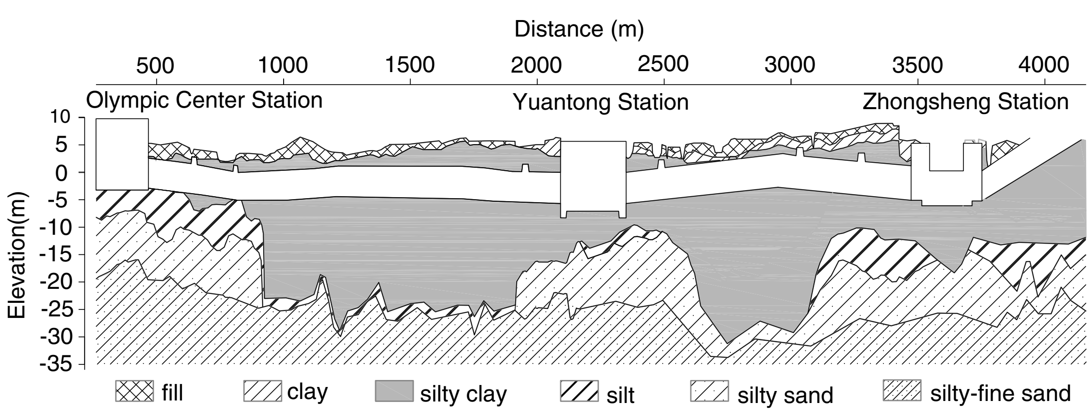

Fig. 3. Geological profile of the west extension of line 1

Table 1. Typical Soil and Soil Properties

Soil		w (%)	γ (kg · m^{-3})	e	I_P	I_L	E_S (MPa)	f_k (kPa)	$k_v \times 10^{-6}$ (cm · s^{-1})
Fill	R	22.7–26.1	19.2–20.0	0.64–0.76	11.8–15.2	0.48–0.71	6.27–8.61	—	—
	Av	24.9	19.6	0.70	13.4	0.56	7.44	—	—
Clay	R	25.8–42.8	17.8–19.9	0.74–1.16	13.0–24.0	0.31–0.86	2.76–7.85	90–120	0.1–0.7
	Av	33.1	18.9	0.91	17.2	0.65	4.96	—	0.4
Silty clay	R	31.9–51.4	16.4–18.7	0.97–1.16	10.0–22.0	1.01–2.15	1.85–5.71	60–80	0.5–6.6
	Av	41.7	18.1	1.18	14.3	1.45	3.16	—	2.2
Silt	R	25.1–39.4	17.7–19.7	0.71–1.13	6.0–12.0	0.80–2.57	4.40–12.38	90–110	5.2–313.0
	Av	32.4	18.6	0.93	9.5	1.44	7.53	—	126.0
Silty sand	R	12.0–26.6	18.9–20.6	0.45–0.77	—	—	15.60–35.21	130–150	55.4–309.0
	Av	19.1	20.0	0.60	—	—	22.41	—	114.0
Silty-fine sand	R	23.0–43.4	17.3–19.5	0.73–1.23	—	—	10.17–24.67	160–220	75.4–609.0
	Av	28.4	18.7	0.87	—	—	15.57	—	304.0

Note: Av = average value; E_s = compression modulus; e = void ratio; f_k = standard value of bearing capacity; I_p = plasticity index; I_L = liquidity index; k_v = vertical permeability coefficient; R = range; r = unit weight; w = moisture content.

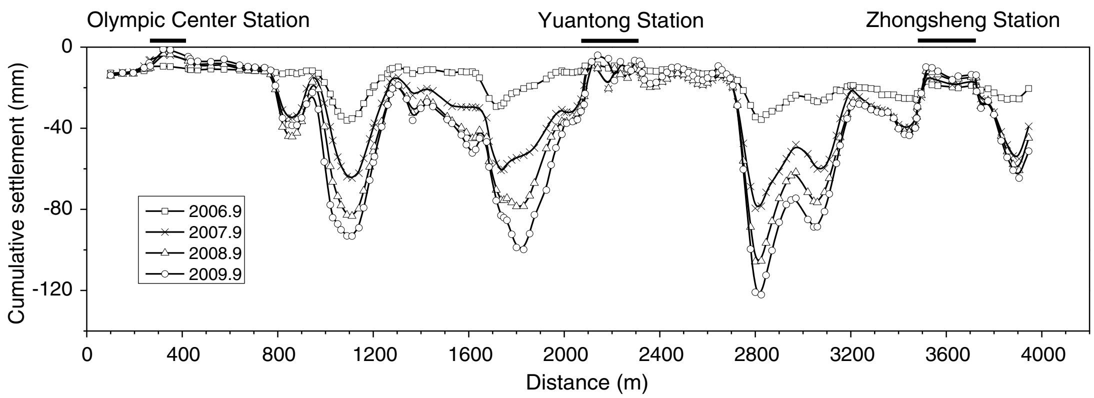

Fig. 4. Observed cumulative settlement of the west extension since operation began

of 4.8 km. It is mainly located in the new city area of western Nanjing, where the recent floodplain soft soil (the soil was predominately formed in the Holocene) is widespread. In this study, the settlement of the underground line (length: 3.94 km) from the Olympic Center Station to the entrance of the Zhongsheng Tunnel (F) was investigated.

Before constructing the cut-and-cover tunnel, the soft ground was strengthened with cement deep-mixing piles (which were 0.5 m in diameter). The pile spacing was 0.75 m, and the depth of the piles was approximately 5 m below the tunnel floor, as shown in Fig. 2. The rectangular tunnel consists of two tubes, each of which has an internal width and height of 4.4 m and 5.16 m, respectively. The thicknesses of the outer walls, middle (dividing) wall, roof, and floor are 0.5 m, 0.3 m, 0.5 m, and 0.6 m, respectively.

Geological Conditions and Soil Properties

Western Nanjing is located on the lower reaches of the Yangtze River, where the alluvial and silted floodplain is widespread and delta-shaped in plain (Xia et al. 2006). Fig. 3 shows the geological profile along the west extension line from Olympic Center Station to the Zhongsheng Tunnel entrance. Most of the tunnel is situated in a layer of silty clay, and the depth of the silty clay underneath the tunnel floor varies considerably (from 0 to 27 m). Between the silty clay and sand layers, there is a scattered thin silt layer.

Table 1 lists the physical and mechanical properties of each layer. The average void ratio, average compression modulus, average permeability in the vertical direction, and standard value of bearing capacity of the silty clay layer are 1.18, 3.2 MPa, 2.2×10^{-6} cm/s, and 60–80 kPa, respectively, which implies that the silty clay layer is characterized by high compressibility, low permeability, and low-bearing capacity. Therefore, without ground improvement, a tunnel constructed in this soft deposit can be expected to have a large total settlement and a large differential settlement following construction, and this settlement may occur over an extended period of time.

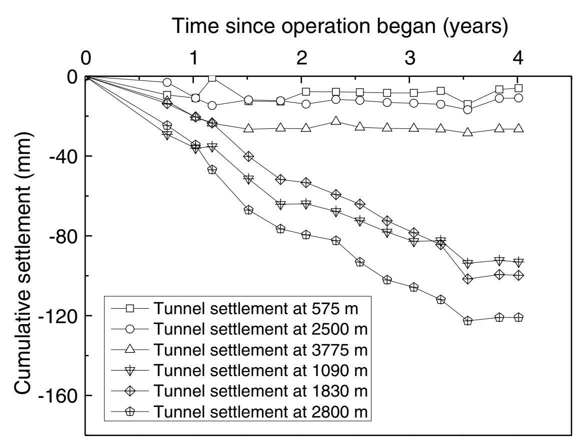

Fig. 5. Tunnel settlement versus time

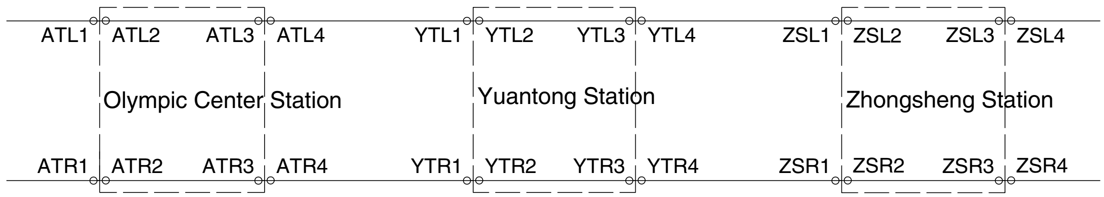

Fig. 6. Layout of measurement points for differential settlement between the tunnel and the stations

Observed Settlement of the West Extension

Settlement monitoring commenced in September 2004. Measurements were taken at average intervals of 25 m along the line, and the leveling points were located on the track bed (Fig. 2).

Variations in Settlement in the Longitudinal Direction of the Line

Fig. 4 shows the observed settlement over a period of four years (from September 2005 to September 2009) since operation began on the west extension. Only the data from the southwest-bound track were analyzed because the observed settlement of both tracks was very similar. The minimum and maximum cumulative settlements measured over four years were 1 mm and 122 mm, respectively. Four troughs resulting from differential settlement were observed in the longitudinal direction of the line, and the differential settlement continued. The large differential settlement was likely caused by the nonuniform distribution of the underlying soft soil. Further details are discussed in the next sections of this paper.

Time History of Tunnel Settlement

Fig. 5 shows tunnel settlement versus time for six locations (at distances of 575, 2,500, 3,775, 1,090, 1,830, and 2,800 m).

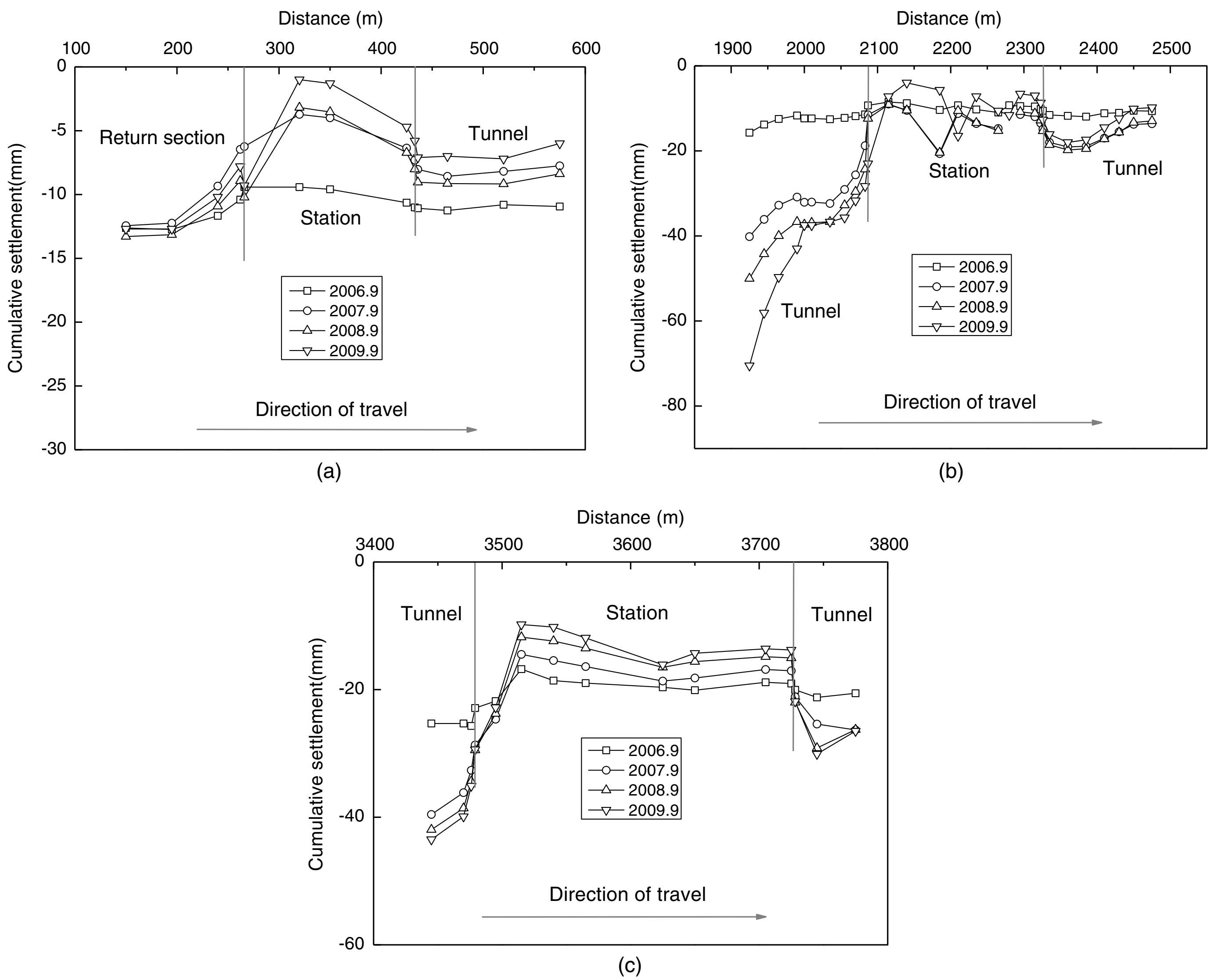

Fig. 7. Differential settlement between the stations and the tunnel: (a) Olympic Center Station; (b) Yuantong Station; (c) Zhongsheng Station

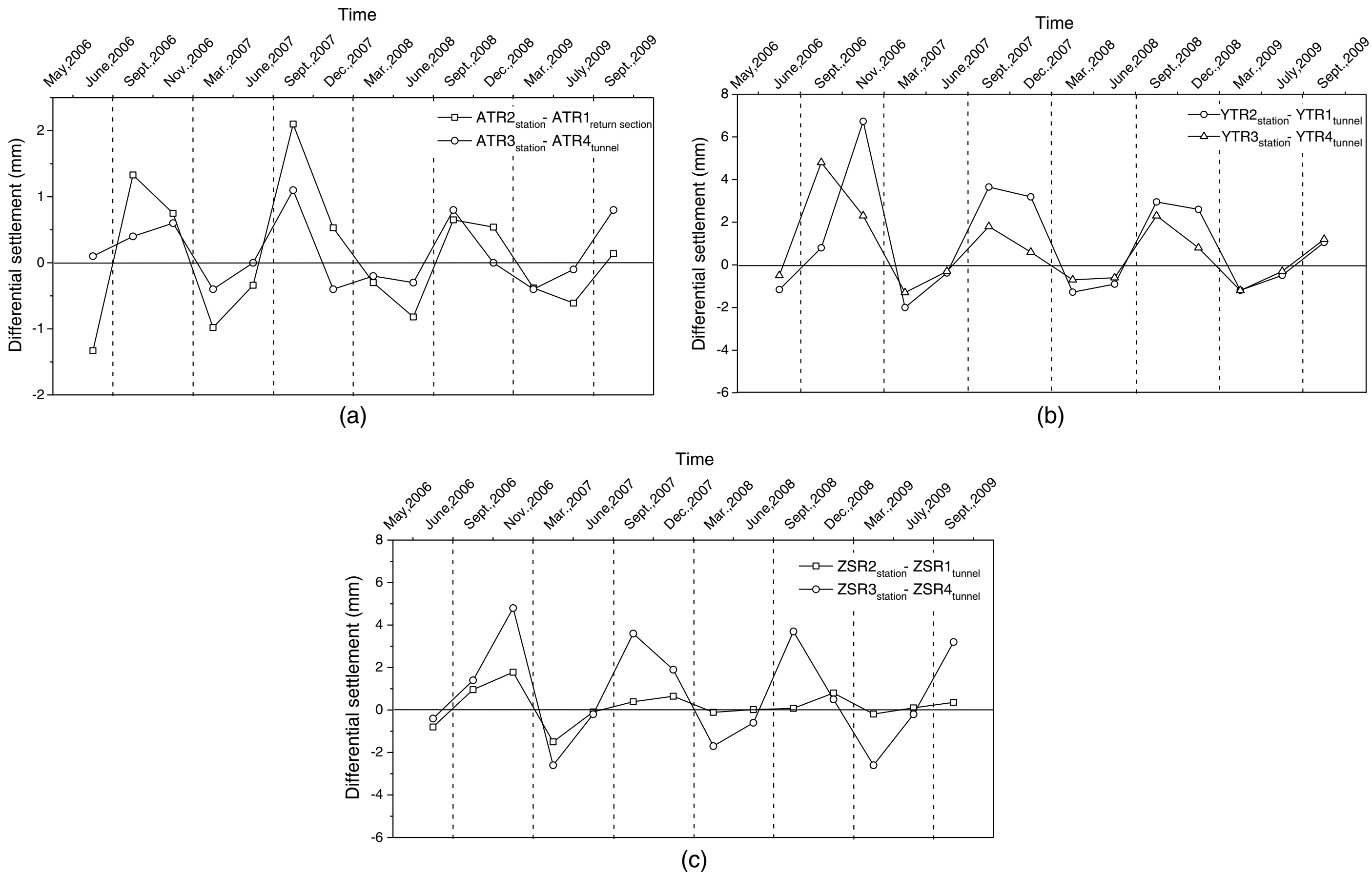

Fig. 8. Differential settlements of station and adjacent tunnel over time: (a) Olympic Center Station; (b) Yuantong Station; (c) Zhongsheng Station

The first three locations are not in the settlement troughs, but the other three locations are. The settlement of the tunnel outside the troughs developed slowly, and it appears to have stabilized. The settlement of the tunnel in the troughs developed rapidly in the first 3.5 years and slowed thereafter, but it does not appear to have stabilized.

Differential Settlement between Stations and Tunnel

To monitor the differential settlement between the stations and the tunnel, measurements were taken at 24 points at the junctions of three stations within the tunnel. The distance between the 2 leveling points was approximately 2–5 m, as shown in Fig. 6.

Fig. 7 shows the differential settlement between the stations and the tunnel (or the return section). The tunnel settlement on each side of the stations varied. In addition, tunnel settlement often led to differential settlement in the interior of the station. The differential settlement was mainly caused by the differences in stiffness between the station and tunnel structures.

Fig. 8 presents the differential settlement between the stations and the tunnel in each monitoring period. The vertical axis is the relative settlement. In general, from December to June, the differential settlement was negative (i.e., the settlement of the station was less than that of the tunnel), and from June to December every year, the differential settlement was positive (i.e., the settlement of the station was greater than that of the tunnel).

This periodic variation was attributed to the structural characteristics and the seasonal variation in the groundwater level. The tunnel is more sensitive to vertical movement due to changes in the groundwater level because the unit-length structural weight of the station is larger than that of the tunnel and because there are uplift piles under the stations, not under the tunnel. Fig. 9 illustrates the variation in the phreatic water level at point I (Fig. 1). The groundwater level is 0.5–1.0 m below the surface. From November to June, the groundwater level gradually decreases, and the amount of settlement in the tunnel is greater than that in the stations. From June to November each year, the groundwater level gradually increases, and the amount of settlement in the tunnel is less than that in the stations due to the action of buoyancy.

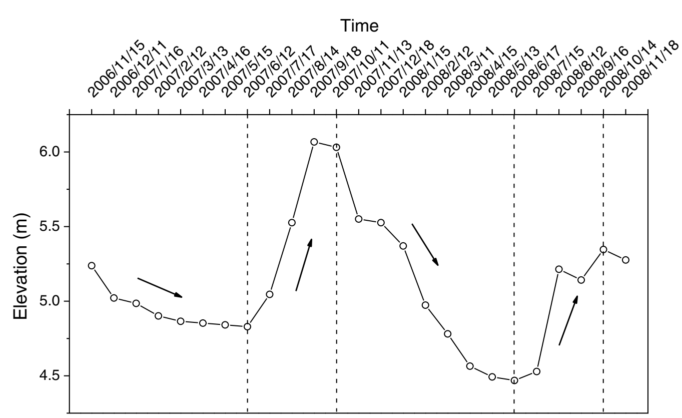

Fig. 9. Phreatic water level at point I versus time

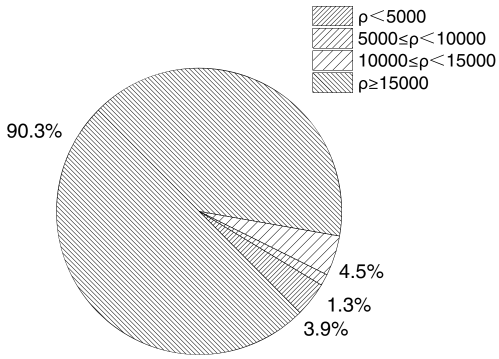

Fig. 10. Curvature radius of settlement

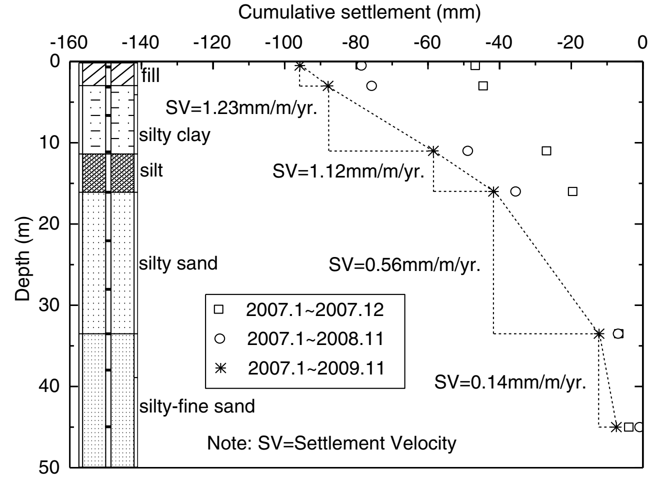

Fig. 12. Compression of the subsoil layers measured from 2007 to 2009

Induced Track and Tunnel Damage

Differential settlement in subway structures results in bending and distortion of the tunnel and the track, causing local cracks and leakage. The water leakage then causes an increase of the effective stress on the soil below the water leakage zone, which accelerates the consolidation settlement of the foundation below the leakage zone. Mud leakage causes loss of soil below the leakage zone and even generates a gap between the tunnel structures and the foundation. Thus, the water and mud leakage in turn accelerates the differential settlement, resulting in a vicious cycle.

Vertical Bending of Tracks

The radius of curvature is a primary parameter for measuring the longitudinal deformation of the tunnel and the distortion of the track. To evaluate the potential risk of differential settlement to the structures, the vertical radius of curvature of the tunnel after settlement was analyzed. This radius can be calculated using the three-point method (Shen et al. 2014). The results are shown in Fig. 10. According to the Technical Code for Protection Structures of Urban Rail Transit [CJJ/T 202-2013 (MOHURD 2013)], the vertical radius of curvature of the tunnel should not be less than 15,000 m. Fig. 10 shows that approximately 10% of the line has a vertical radius of curvature that violates this safety limit.

Cracking and Leakage

To evaluate the condition of the structures, crack and leakage inspections were performed. Most cracks and leakage were positioned in settlement troughs, and the crack widths varied from 0.1 to 0.5 mm. These cracks can be classified into three types: (1) transverse cracks in the tunnel roof; (2) transverse cracks in the tunnel floor (track bed); and (3) inclined cracks in the outer wall. The cracks and leakage were mainly caused by the differential settlement. In general, the longitudinal differential settlement results in two types of bending moment in the tunnel structure: convex

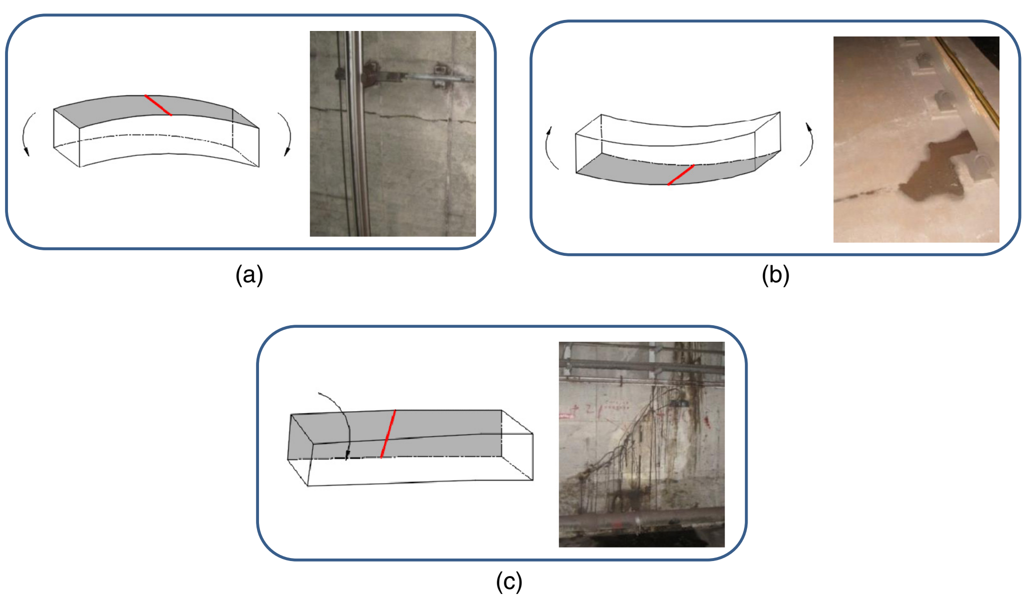

Fig. 11. Structural damage in the line: (a) transverse cracks in the tunnel roof; (b) transverse cracks in the tunnel floor and track bed; (c) inclined cracks in the outer wall

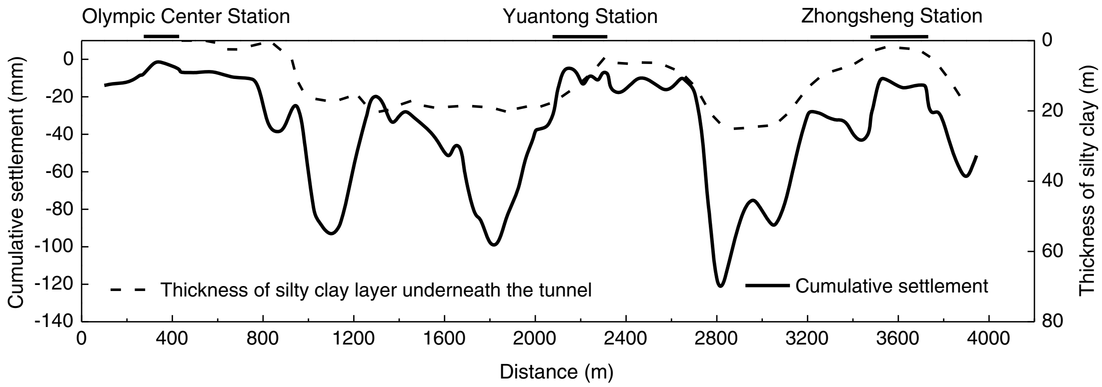

Fig. 13. Comparison between cumulative settlement and thickness of silty clay under structures

bending and concave bending (Fig. 4). Convex bending induces compression stress in the tunnel floor and tension stress in the tunnel roof, which tends to result in cracks in the tunnel roof, as shown in Fig. 11(a). Concave bending induces compression stress in the tunnel roof and tension stress in the tunnel floor, which tends to result in cracks in the tunnel floor, as shown in Fig. 11(b). In addition, the adjacent construction activities, such as local excavation and reloading, may lead to the imbalance of earth pressure on both sides of the tunnel, as well as differential settlement in both the longitudinal and transverse directions, which will cause bending and twisting of the tunnel. Under the combined action of bending-shear-torsion, inclined cracks occur in the outer wall, as shown in Fig. 11(c).

Main Causes of Differential Settlement

To analyze the causes of the differential settlement of the west extension, the settlement velocity (SV, unit: mm/m/year) of subsoil layers measured from 2007 to 2009 at location II (Fig. 1) was illustrated in Fig. 12. SV is defined as the annual average settlement in unit thickness of each soil layer. It was observed that the settlement velocities of the silty clay layer and silt layer (1.23 mm/m/year and 1.12 mm/m/year, respectively) were much larger than those of the silty sand and silty fine-sand layers.

Fig. 13 shows the correlation between the cumulative settlement and the thickness of the silty-clay layer underneath the tunnel. This graph demonstrates that the locations where the soft silty-clay layer is thicker often exhibited more settlement than those where the soft silty-clay layer is thinner. These differences occur because the locations where the soft silty-clay layer is thicker undergo larger recompression deformations and larger secondary compression after construction and because of larger induced settlement from cyclic train loads when service begins (Wu et al. 2014). Moreover, due to the poor engineering properties of the soft silty-clay layer, the tunnel foundation in those locations is much more susceptible to settlement caused by disturbances from adjacent construction activities (Tan et al. 2014). Thus, the nonuniform distribution of the soft silty clay layer along the line is the main cause of the larger differential settlements.

From the preceding analysis, it can be deduced that the deep mixing piles used to improve the foundation of this line are not sufficiently deep to restrict the long-term tunnel settlement. For future cut-and-cover tunnel construction in the new city area of Nanjing, improved design methods, including more accurate predictions of settlement and estimates of the soil treatment depth for foundations, should be developed.

Conclusions

The characteristics and causes of the differential settlement in the west extension of Nanjing Metro Line 1 were analyzed in this study, and the following conclusions can be drawn:

1. The minimum and maximum cumulative settlements measured during four years of operation were 1 mm and 122 mm, respectively. Four settlement troughs formed in the longitudinal direction of the line, and a periodic variation of differential settlement between the stations and the tunnel was observed.
2. The differential settlement has caused bending and distortion of the tunnel and track structures. In approximately 10% of the line, the vertical radius of curvature is less than the safety limit of 15,000 m. Three typical kinds of cracks and water leakage have occurred in the tunnel and track structures, and the crack widths vary from 0.1 to 0.5 mm.
3. The nonuniform distribution of underlying soft soil is the main cause of the differential settlement of the line. The periodic variation of differential settlement between the stations and tunnel was attributed to the structural characteristics of the stations and tunnel as well as the seasonal variation in the groundwater level.

Acknowledgments

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