Identification of Tunnel Settlement Caused by Land Subsidence in Soft Deposit of Shanghai

Huai-Na Wu[1]; Shui-Long Shen[2]; and Jun Yang, F.ASCE[3]

Abstract: This paper provides a straightforward way to evaluate tunnel settlement caused by land subsidence in the soft deposits of Shanghai. By analyzing field measurements of tunnel settlement and land subsidence, it was found that the tunnel settlement was caused by ground subsidence under the tunnel, and was unrelated to the compression of the upper soil layers. Because significant compaction of the upper layers can occur due to urban construction, the measured land subsidence, which is the ground surface subsidence, cannot represent the sublayer subsidence. To solve this problem, this paper takes metro stations as the monitoring point at the depth of the tunnel, and uses a cubic spline function to fit the line of the station points. The derived fitting curve is then used to represent the ground subsidence under the tunnels. The rationality of taking the stations as monitoring points is verified based on a load transfer analysis. The proposed method is applied to investigate the settlement of metro tunnels in Shanghai. It was found that land subsidence–induced settlement accounts for 62.5% of the maximum cumulative settlement in some sections of Metro Lines No. 1 and No. 2 up until 2010. **DOI: 10.1061/(ASCE)CF.1943-5509.0001082.**

Author keywords: Metro tunnel; Settlement; Land subsidence; Station; Shanghai.

Introduction

Shanghai's metro system has been undergoing construction since the 1980s. By the end of 2015, there were 14 lines and 332 stations with a total mileage of 538 km in operation. Of these lines, more than 50% were constructed underground, with a burial depth of about 9 to 15 m. These metro tunnels were generally excavated using the shield-driven method, in which the lining is composed of precast concrete segments connected by steel bolts. During long-term operation, the metro tunnels in Shanghai have been subjected to significant settlement and great differential settlement. For example, the maximum settlement of Shanghai Metro Line No. 1, which was opened in 1995, reached about 295 mm after 15 years of its opening. The maximum settlement of Metro Line No. 2, which was opened in 1999, reached about 170 mm by 2010 (Wang 2009; Wang et al. 2013; Shen et al. 2014). Large differential settlement has led to leakage of groundwater, distortion of tracks, and separation between ballastless beds and linings, and it may even bring a risk to train safety (Shen et al. 2014; Wu et al. 2013, 2015a).

The mechanism of long-term settlement of metro tunnels has become an issue of great concern. Many factors contributing to tunnel settlement have been identified, including land subsidence, postconstruction consolidation and secondary consolidation, cyclic loading of running trains, groundwater leakage, and disturbance from nearby construction (Lee et al. 1999; Wongsaroj et al. 2007; Mair 2008; Shin et al. 2002, 2012; Chen et al. 2013; Tan and Lu 2016; Tan et al. 2016; Shen et al. 2014, 2016, 2017; Wu et al. 2014; Ye et al. 2015). Generally, tunnel settlement does not result from the action of a single factor, but from the interaction of many factors. Therefore, in most cases the various causes of the tunnel settlement become indistinguishable. In order to control tunnel settlement in a targeted manner, it is necessary to identify the influence of each factor.

Shanghai is located on the deposit of the Yangtze River deltaic, adjacent to the East China Sea. The bedrock in Shanghai is buried under Quaternary and Tertiary sediments with a thickness greater than 300 m (Xu et al. 2009). The Quaternary deposit in Shanghai consists of a phreatic aquifer group (Aquifer 0, hereafter called Aq0) and five artesian aquifers (Aquifer I–Aquifer V, hereafter called AqI–AqV) that are separated by six aquitards (Aquitard I–Aquitard V, hereafter called AdI–AdVI). The details of the forming era and the sedimentary environment of each stratum can be found in several publications of the authors' research group (Xu et al. 2009, 2012, 2013; Shen and Xu 2011). As in many coastal cities, land subsidence is a serious problem in Shanghai (Figueroa Vega 1976; Galloway et al. 1999; Gambolati et al. 2006; Pavelko et al. 2006; Chai et al. 2004; Xu et al. 2009, 2016; Wu et al. 2015b). The phenomenon of land subsidence in Shanghai was observed as long ago as 1921. Up to now, the cumulative land subsidence has reached 2–3 m in the urban area (Xu et al. 2015). The cause of the land subsidence in Shanghai has been shown to be the excessive pumping of groundwater and the construction of municipal facilities and high-rise buildings (Xu et al. 2012, 2013, 2014, 2015). Buried in the soft deposit of Shanghai, shield tunnels will inevitably deform with the land subsidence. Uneven land subsidence will lead to a differential settlement of metro tunnels. Some previous publications

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have reported a certain correlation between land subsidence and tunnel settlement (Chen and Zhan 2000; Ye et al. 2007; Wang et al. 2013). However, because of interactions with other factors, the influencing weight of land subsidence remains uncertain.

This paper aims to evaluate the influence of land subsidence on the long-term settlement of metro tunnels in the soft deposits of Shanghai. The detailed objectives are (1) to propose an evaluation method for tunnel settlement induced by land subsidence and (2) to identify the influencing weight of land subsidence on tunnel settlement in Shanghai.

Land Subsidence in Shanghai

Fig. 1 shows land subsidence in the urban area of Shanghai from 1921 to 2010. The development of land subsidence in Shanghai can be divided into three phases: (1) rapid development phase (1921–1965), (2) stabilized phase (1966–1985), and (3) accelerated phase (1985–2010). Construction of the first metro tunnel in Shanghai, Metro Line No. 1, commenced in the 1980s and the line went into operation in 1995, which is in the accelerated phase of land subsidence. Fig. 2 gives a contour plot of land subsidence in the urban area of Shanghai since 1996. As shown in Fig. 2(a), between 1996 and 2000, citywide accelerated subsidence occurred, with an average rate of 25 mm per year. The cumulative subsidence in the urban area was generally greater than 75 mm, reaching 200 mm in some places. From 2001 to 2005, the land subsidence slowed down, and had an average rate of 13 mm per year in this period, as shown in Fig. 2(b). The large-scale subsidence funnel had disintegrated into many small isolated subsidence funnels, the center of which may have reached 150 mm. During the period from 2006 to 2010, the cumulative subsidence was generally controlled to within 50 mm, although in some scattered places there was subsidence greater than 100 mm, as shown in Fig. 2(c).

The main activity causing land subsidence in Shanghai is the excessive pumping of groundwater, which causes drawdown of the water table in the aquifers (Chai et al. 2004; Shen and Xu 2011; Xu et al. 2012, 2013, 2014, 2015). Before 1965, groundwater was mainly pumped from AqII and AqIII. Land subsidence had a good correlation with the withdrawn volume of groundwater. Since 1966, in order to control land subsidence, the pumping layer was changed to AqIV and AqV, and the pumping volume was greatly reduced with an increase in recharge. After 1985, with the rapid urbanization of Shanghai, the increasing demand for groundwater led to a significant increase in pumping volume. In this period, the pumping wells were mostly transferred from the urban area to the suburbs. In the urban area, the recharge volume exceeded the pumping volume. However, as the groundwater in Shanghai flows from west to east, pumping from the western suburbs has led to a reduction in replenishment to the urban area, causing a reduction in the water table and the acceleration of land subsidence in the urban area. In addition, large-scale urban construction accompanied by urbanization has also contributed to land subsidence. The influential factors of urban construction include the additional load associated with construction, the change in the seepage field due to the cutoff effect of underground structures in aquifers, the decline of the groundwater level due to leakage in underground structures, and the reduction in recharge of groundwater from the surrounding areas (Xu et al. 2009, 2012, 2013, 2014, 2015; Yin et al. 2011, 2013a, b; Shen et al. 2013a, b, c; Ma et al. 2013).

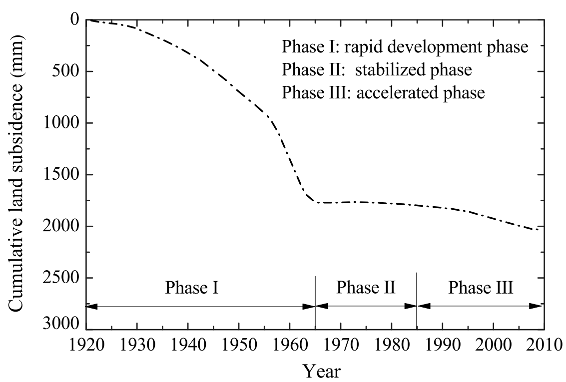

Fig. 1. Cumulative land subsidence with elapsed time in Shanghai (adapted from Xu et al. 2012)

Comparison between Land Subsidence and Tunnel Settlement

Fig. 3 shows the measured cumulative settlement of the uplines of Metro Line No. 1. Settlement has increased over the years since it began running in 1995. Significant differential settlement occurred in the longitudinal direction, with the maximum being 295 mm near the People's Square Station, and the minimum being 0.8 mm near the Shanghai Indoor Stadium Station. Two large settling basins formed around the Hengshan Road Station and from South Huangpi Road Station to Xinzha Road Station.

Fig. 4 gives a comparison between the tunnel settlement of Metro Line No. 1 and the land subsidence along the tunnel axis during different periods. It can be seen that between 1995 and 2000 the land subsidence was serious (50–100 mm) and the tunnel settlement in the same period was large, with a maximum of about 180 mm. Between 2006 and 2010, the land subsidence was controlled to within 50 mm, and the tunnel settlement in the same period was also small, generally less than 25 mm. It is also evident that the spatial pattern of land subsidence determines the spatial developing trend of the tunnel settlement. For the same period, the settlement trough of the tunnel was located in the area that suffered serious land subsidence. A correlation analysis for the tunnel settlement and the land subsidence was conducted (as shown in Fig. 5). The data were extracted from Fig. 4 with a spacing of 500 m in the longitudinal direction, and the correlation between the two is reflected using Pearson's correlation coefficient (Pearson 1895). It can be seen that the Pearson's correlation coefficient in Fig. 5 is about 0.87, which indicates the tunnel settlement curves are highly correlated with land subsidence.

Fig. 6 gives a comparison of tunnel settlement near the Zhongshan Park Station of Metro Line No. 2, showing the layered ground subsidence varying with time. The tunnel base is located at a depth of 16 m. It can be seen that both ground subsidence and tunnel settlement increased over time. The rates of tunnel settlement are closely related to subsoil subsidence over the same time period. The subsidence of the ground surface was greater than the tunnel settlement, and the difference increased with time. Soil compression above the tunnel seems to have less effect on tunnel settlement. For example, the section between Century Avenue Station and Pudian Road Station on Shanghai Metro Line No. 4 had a cumulative settlement of about 2.0 to −1.9 mm (i.e., uplift) from June 2009 to December 2010, whereas the land subsidence over the same period reached 20 mm. According to the field measurements on layered subsidence, the land subsidence in the field is mainly caused by compression of the soils above the tunnel. Therefore, it can be concluded that tunnel settlement is correlated with sublayer settlement rather than with ground surface subsidence.

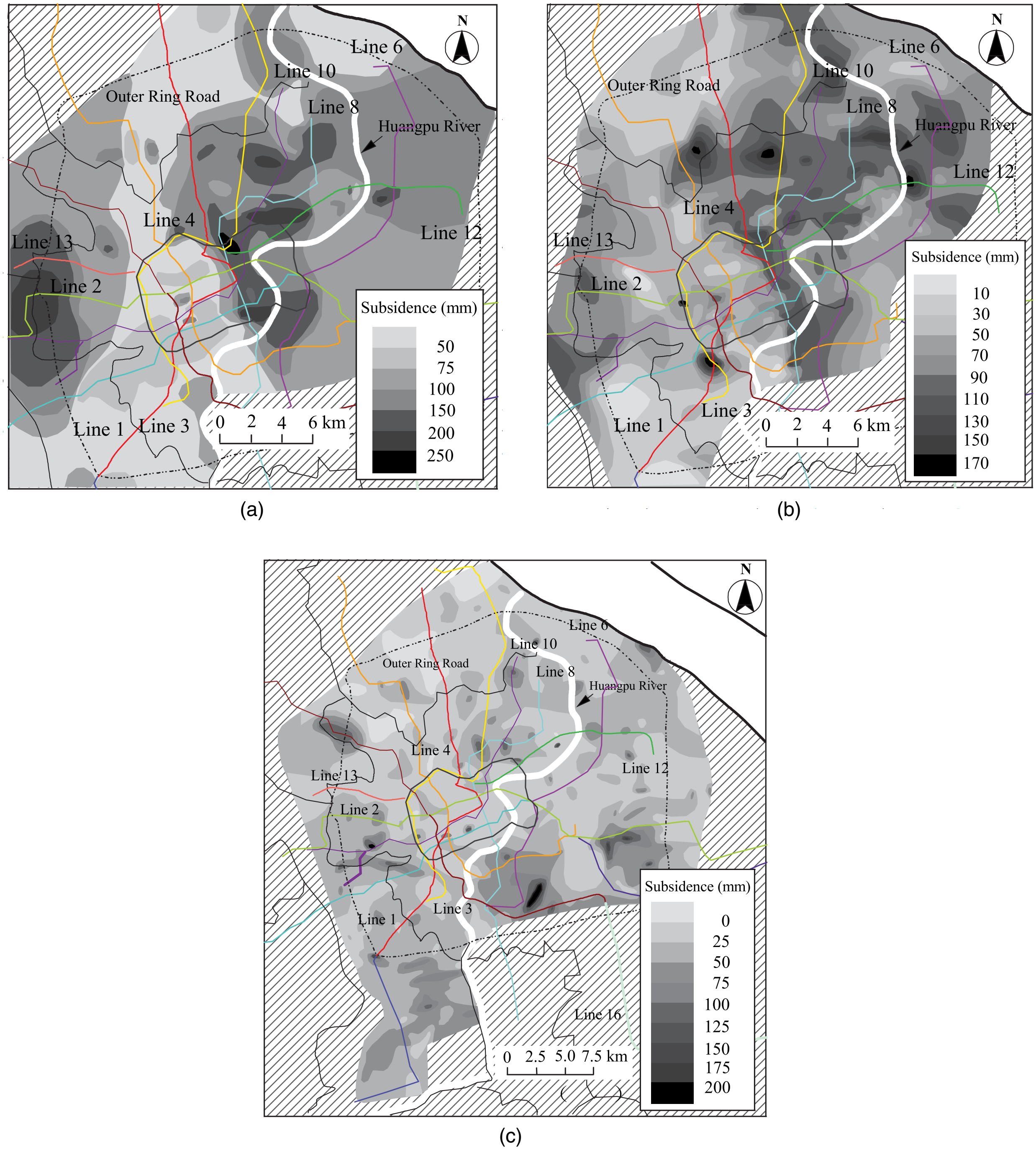

Fig. 2. Land subsidence contour in Shanghai in periods from 1996 to 2010 (data from SSMRC 2012): (a) 1996–2000; (b) 2001–2005; (c) 2006–2010

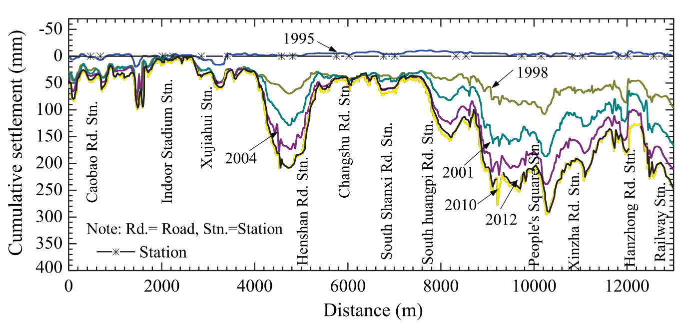

Fig. 3. Measured settlement profiles of the upline of Metro Line No. 1 in Shanghai (data from SSMRC 2012; Wu et al. 2015a)

Evaluation of Tunnel Settlement Caused by Land Subsidence

In view of the difference between land subsidence and tunnel settlement, to obtain the tunnel settlement caused by land subsidence, it is preferable to conduct field measurements of the layered subsidence rather than the ground surface subsidence. Shanghai has a dense citywide subsidence monitoring network, which includes precise leveling and GPS monitoring (SMBPL 2015). However, layered subsidence monitoring points are distributed less densely. There are currently 48 sets of layered subsidence monitoring points in Shanghai, most of which are located some distance from the metro tunnels (SMBPL 2015). Therefore, it is still difficult to evaluate the tunnel settlement caused by land subsidence using the

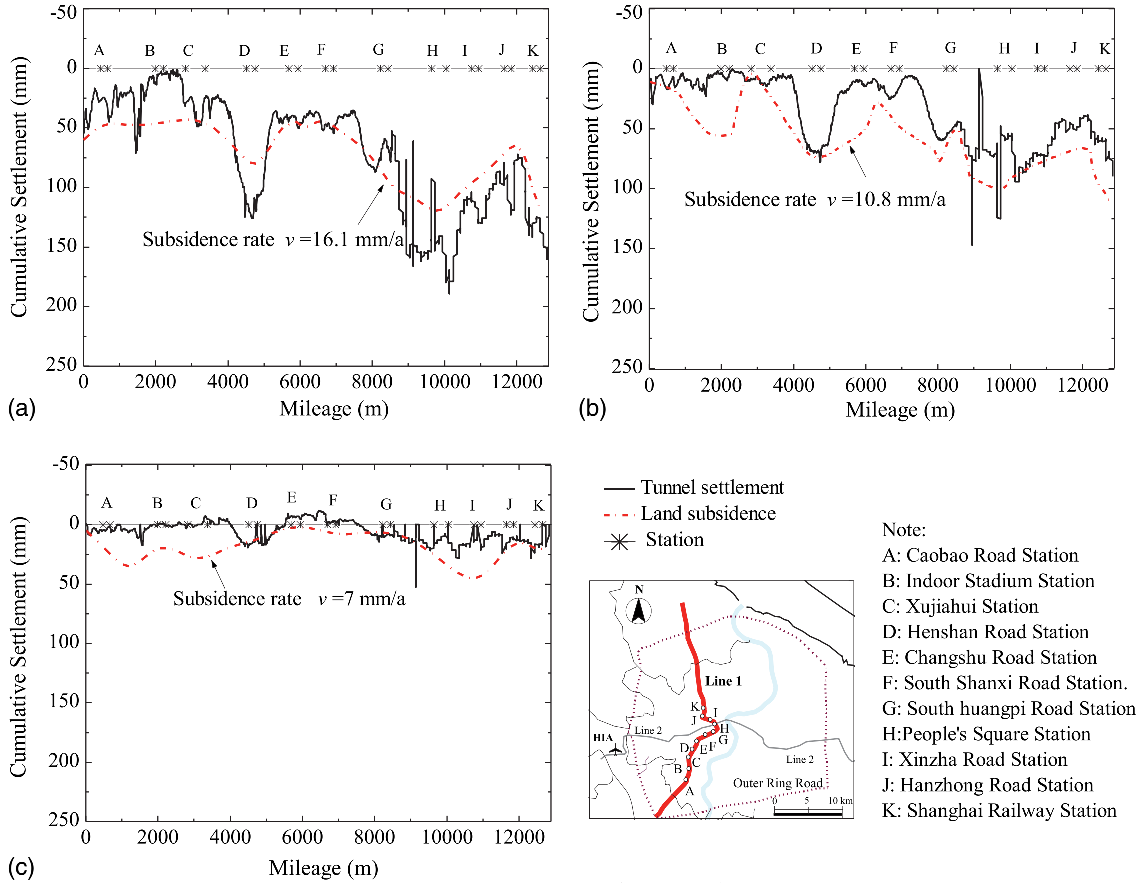

Fig. 4. Comparison of tunnel settlement and land subsidence along Metro Line No. 1 (adapted from Shen et al. 2014): (a) 1995–2000; (b) 2001–2005; (c) 2006–2010

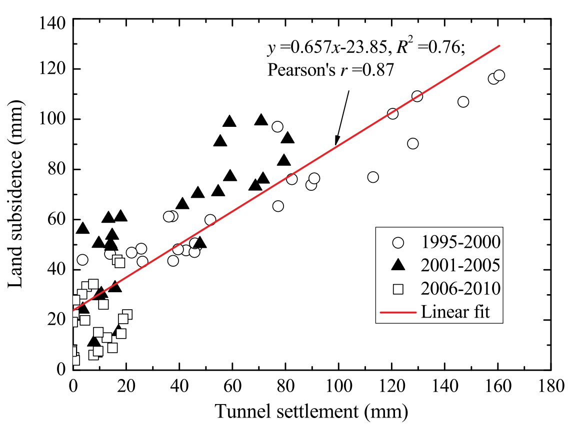

Fig. 5. Correlation between tunnel settlement and land subsidence

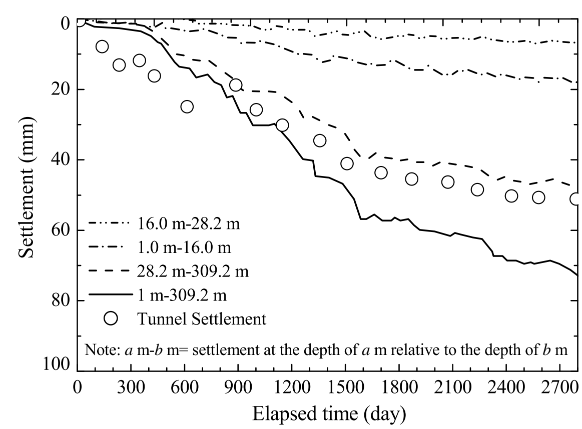

Fig. 6. Comparison between tunnel settlement and layered ground subsidence (data from SSMRC 2012)

layered monitoring system in Shanghai. In this paper, the settlement of metro stations is analyzed. Based on the analysis results, a simple method to evaluate the tunnel settlement caused by land subsidence is proposed.

Observed Station Settlement

There are clear differences between the different stations in the settlement recorded. Shanghai Stadium Station settled at a magnitude of about 10–20 mm, whereas People's Square Station had a magnitude of settlement of 210–240 mm, as shown in Fig. 1. Fig. 7 shows the settlement of Xinzha Road Station varying with time. Between 1999 and 2007, each station settled uniformly. Also, it is evident that settlement of the stations varied seasonally, with a higher rate in the summer season and a lower rate in the winter season. Such variation is consistent with that of land subsidence in Shanghai, which is related to the local government control of groundwater extraction and recharge. In Shanghai, the groundwater

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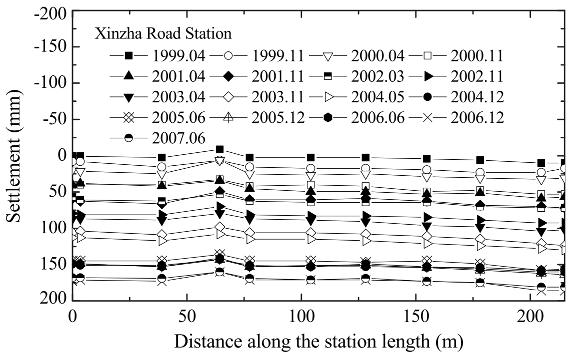

Fig. 7. Settlement of stations in periods (data from SMOCCB 2007)

is pumped from July to September, and is recharged from December to April.

Mechanisms of Station Settlement

The settlement of stations during long-term operation can be attributed to the following causes: (1) land subsidence and (2) compression of subsoil due to train load and pedestrian load. Buried in the ground, stations will inevitably suffer from settlement where there is land subsidence. Tunnel settlement due to the compression of subsoil associated with train load and pedestrian load is discussed subsequently, taking one Shanghai station as an example.

Formulation of Problem

Fig. 8 gives a cross-sectional view of a station on Metro Line No. 11, and the corresponding soil profile in the field. The station is an underground structure with three stories. It is situated at a depth of 19.6 m below the ground surface. The total length of the station is 170 m. A continuous diaphragm wall up to a depth of 37 m has been constructed to form the permanent walls of the station. The soil layers of the upper 37.8 m are as follows: The top of the deposit is a silty clay layer with a thickness of 4.6 m. Below that is a very soft silty clay layer with a thickness of 4.4 m, followed by an 8-m-thick very soft clay layer. These two layers are characterized by high water content, high compressibility, low permeability, and low shear strength. The next layer is a clay layer with a thickness of 18 m. Following this is a stiff clay layer with a thickness of 2.8 m. The unit weight and the lateral earth pressure coefficient for each layer are given in Fig. 8.

Load Analysis

During the construction and long-term operation of a station, the subsoil beneath the station will experience the following steps: (1) unloading due to excavation of the foundation pit, leading to swelling of the subsoils; (2) loading due to construction of the station, causing compression of the subsoils; and (3) reloading due to the train load and the pedestrian load during operation, leading to recompression of the subsoils. The load for each step can be calculated as follows:

Step I: The unloading due to excavation of the foundation pit can be calculated as

$$\Delta p_1 = \sum \gamma_i H_i = -147.94\ \text{kN/m}^2 \qquad (1)$$

where Δp_1 = unloading due to excavation of foundation pit; γ_i = unit weight of Layer i ($i = 1, 2, \ldots, n$; n = number of soil layers above bottom of foundation pit); and H_i = thickness of Layer i.

Step II: The unit weight of the station is assumed to be 25 kN/m^3. The calculated weight of the station and overburden (labeled as F_{stn}), including the weights of the roof, baseboard, walls, diaphragm wall, floors, pillars, covering soils, and overcharge on the ground, is 5,232.87 kN/m. The buoyancy of the station (labeled as f_{stn}), is calculated as $f_{\text{stn}} = (15.087 - 3.7) \times 10 \times 25.5 = 4{,}790.69$ kN/m. Then, the loading on the subsoil due to construction of the station (labeled as F') can be obtained, which is $F' = F_{\text{stn}} - f_{\text{stn}} = 5{,}232.87 - 4{,}790.69 = 442.18$ kN/m. The equivalent loading pressure on the subsoil (labeled as Δp_2) is $\Delta p_2 = 442.18/25.5 = 17.34\ \text{kN/m}^2$.

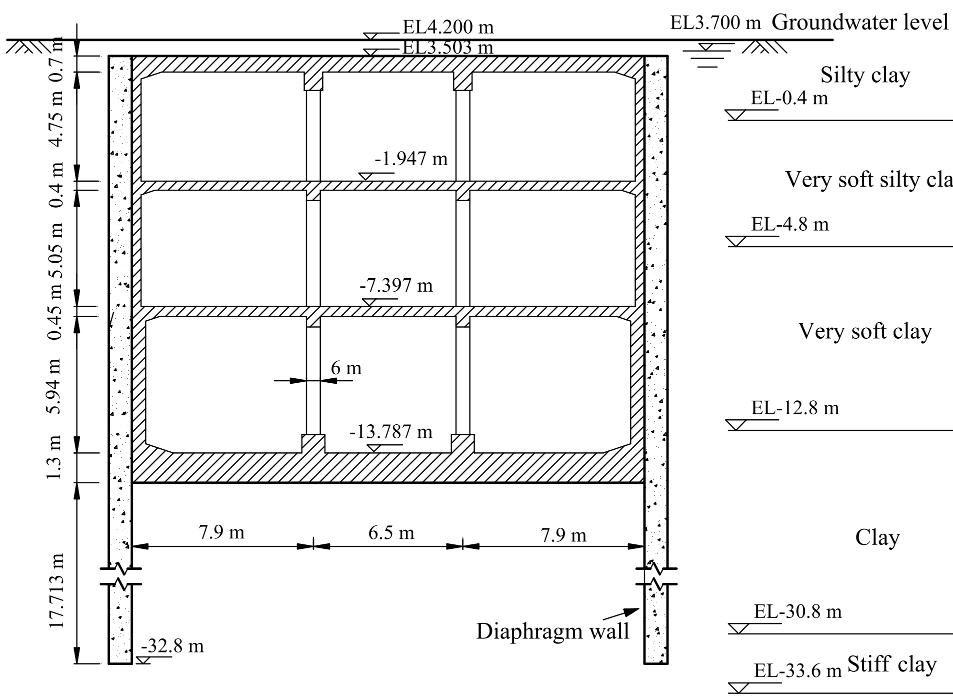

Fig. 8. Cross-sectional view of metro station

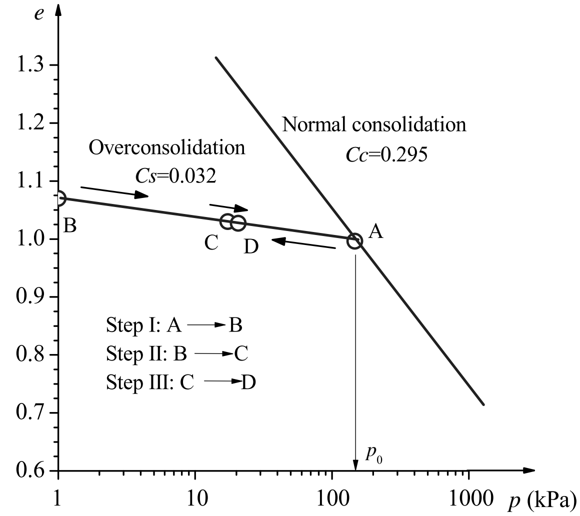

Fig. 9. Idealized compression and swelling of soils under station

Step III: During long-term operation, the pedestrian load can be evaluated by the designed load (4 kPa for the platform, hall, and stairs) with a quasi-permanent coefficient of 0.5 (MOHURD 2012). Trains with eight carriages and an axle load of 16,000 kg are considered. The train load transferred to the soils at the base of stations is $[(160 \times 32)/180] \times 2/25.5 \times 0.6 = 1.3\ \mathrm{kN/m^2}$. The total load for Step III (labeled as Δp_3) equates to the sum of the train load and the pedestrian load, which is 3.3 kPa.

Calculation of Settlement

Fig. 9 shows an idealized model of compression and swelling of the subsoils under a station during loading and unloading. The slopes of the normal consolidation line, C_c, and the overconsolidation line, C_s, are 0.295 and 0.032, respectively. Assuming that the soils are in a normally consolidated state before construction, the initial stress corresponds to Point A (Fig. 9). During excavation (Step I), the subsoil is unloaded, and its state will be on the overconsolidation line AB. After completion of excavation, the soil is at Position B, where the stress tends to be zero and the void ratio is 1.07. During construction of the station (Step II), the soil is loaded and its state moves from Point B to Point C, which is in an overconsolidated state. The void ratio reduces to 1.03 after construction. During long-term operation, the soil is reloaded, and its state moves from Point C to Point D along the overconsolidation line. The void ratio then reduces to 1.027.

The compression of the soils during long-term operation (Step III) can be calculated by the layerwise summation method, which is expressed in the following equations for overconsolidated soils:

$$S = \sum_{1}^{N} S_i \tag{2}$$

$$S_i = -\frac{\Delta e_i}{1 + \Delta e_{0i}} H_i = \frac{H_i}{1 + e_{0i}} C_{si} \log\left(\frac{p_{0i} + \Delta p_{0i}}{p_{0i}}\right) \tag{3}$$

where S = total compression of soil under station; N = number of layers divided for calculation; i = layer number, $i = 1, 2, \ldots, N$; S_i = compression of Layer i; p_{0i} = average stress of Layer i; Δp_{0i} = stress increment of Layer i; H_i = thickness of Layer i; e_{0i} = initial void ratio of Layer i; Δe_{0i} = variation of void ratio of Layer i; and C_{si} = swelling index of Layer i. The variation in stress attenuation with depth can be calculated based on the method proposed by Osterberg (1957). Table 1 presents the detailed calculation of after-construction settlement. It is worked out that the settlement caused by the train load and the pedestrian load during operation is about 1.87 mm.

Evaluation Method of Tunnel Settlement Caused by Land Subsidence

Based on the aforementioned analysis, a simple method to evaluate tunnel settlement due to land subsidence is proposed. The method takes the stations as the monitoring point at the depth of the tunnel, and the detailed steps are as follows: (1) use a Cartesian coordinate system with the longitudinal distance along the tunnel as the x axis, and settlement as the y axis; (2) plot the scatter points of the station settlements, $P_i(x_i, y_i)$, where i is the station number and $i = 1, 2, \ldots, n$; P_i is the coordinate of Station i; x_i is the mileage of the station; and y_i is the settlement of Station i; and (3) use a cubic spline function to fit the line of the station points, and the derived fitting curve, expressed as $y = s(x)$, represents the ground subsidence under the tunnels. Fig. 10 gives a schematic diagram of the calculation method. The cubic spline is defined as follows:

For the given control points $P_i(x_i, y_i)$, $x_i < x_{i+1}$; $i = 1, 2, \ldots, n$; and the cubic spline $y = s(x)$ satisfies the following conditions:

1. For each control point P_i, $y_i = s(x_i)$;
2. The term $s(x)$ is both continuous and continuously differentiable to order 1 and 2 at the interior points x_i, $i = 1, 2, \ldots, n$. That is, $s(x_i - 0) = s(x_i + 0)$, $s'(x_i - 0) = s'(x_i + 0)$, and $s''(x_i - 0) = s''(x_i + 0)$;
3. For each interval $[x_i, x_{i+1}]$, $s(x)$ is constructed of piecewise third-order polynomials. That is, $s(x) = c_{i1}(x - xi)^3 + c_{i2}(x - x_i)^2 + c_{i3}(x - x_i) + c_{i4}$, where c_{i1}, c_{i2}, c_{i3}, and c_{i4} are constants.

The proposed method can be implemented using the commercial software *MATLAB*. Because the ground subsidence below the tunnel is mainly caused by pumping from deep aquifers (e.g., AqIV, AqV), the settlement curve will be in accord with the variation in the water tables of the aquifers. The scope of the drawdown is usually very large (Shen et al. 2013a), and no sudden change in the settlement curve can occur. The ground subsidence curve at the depth of the tunnel should be a smooth line. In Shanghai, the distances between adjacent stations are between 0.8 and 1.2 km, which is small enough to guarantee an acceptable sampling density.

Table 1. Calculation for After-Construction Settlement

Layer	Thickness H_i (m)	Initial average stress p_i (kPa)	Average additional stress Δp_i (kPa)	Total stress after loading p_i' (kPa)	Variation of void ratio Δe_i	Compression S_i (mm)
1	2	24.94	2.45	28.24	0.001302	1.283
2	2	40.14	1.2	41.74	0.000409	0.403
3	2	55.34	0.55	56.14	0.000137	0.135
4	2	70.54	0.2	70.84	3.93×10^{-5}	0.039
5	2	85.74	0.075	85.84	1.22×10^{-5}	0.012
Total						1.872

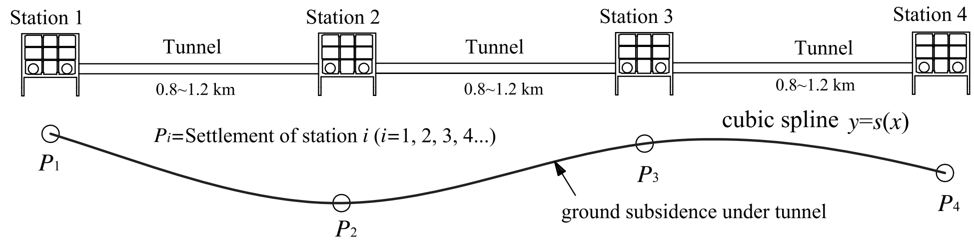

Fig. 10. Schematic diagram of calculation method of ground settlement under tunnel

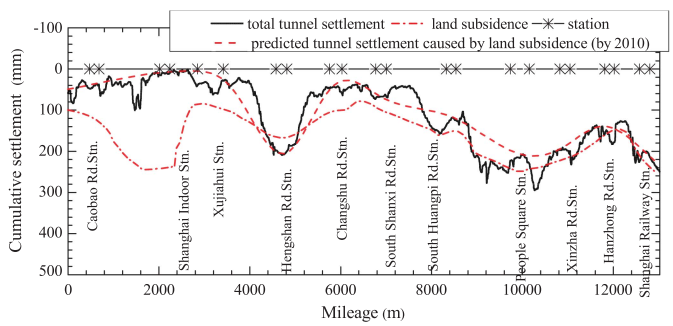

Fig. 11. Cumulative tunnel settlement of Line No. 1 caused by land subsidence

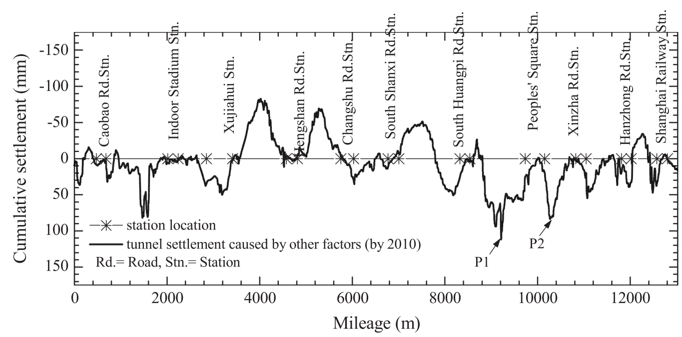

Fig. 12. Cumulative tunnel settlement of Line No. 1 caused by factors except land subsidence

Therefore, it is reasonable to use a cubic spline passing through station settlement points to present the ground subsidence under the tunnel, which is the tunnel settlement caused by land subsidence.

Case Studies of Metro Tunnels in Shanghai

The proposed method was adopted to evaluate the tunnel settlement caused by land subsidence in Shanghai Metro Lines No. 1 and No. 2, and the influence of land subsidence is discussed.

Shanghai Metro Line No. 1

Fig. 11 shows the measured tunnel settlement of Metro Line No. 1 up until 2010, and the calculated tunnel settlement caused by land subsidence based on the proposed method. The land subsidence above the tunnel is also presented in Fig. 11. As shown in the figure, the calculated ground subsidence under the tunnel is generally less than the measured land subsidence, except in the sections near Hengshan Road Station. Both subsidence lines present similar trends, which indicates the proposed method is reasonable. The land subsidence from Caobao Road Station to Xujiahui Station is much greater than the predicted ground subsidence at the depth of the tunnel. This may be attributed to the following causes: (1) significant compression of the upper layers due to large-scale construction or (2) errors in the measurement of land subsidence. The reason for the land subsidence in Hengshan Road Station being smaller than the subsidence below the tunnel may be (1) uplift of upper layers due to excavation, (2) errors in the measurement of land subsidence, or (3) errors in the measurement of the station settlement. The curve of land subsidence along the tunnel is obtained from the regional subsidence contour. There may be some errors if the measuring points are not located directly above the tunnel.

By subtracting the tunnel settlement caused by land subsidence from the total settlement, the tunnel settlement induced by other factors (disturbance from nearby construction, groundwater infiltration, postconstruction settlement induced by tunneling disturbance, cyclic load of trains) can be obtained. Fig. 12 shows the tunnel settlement of Metro Line No. 1 caused by other factors from 1995 to 2010. It can be seen that the settlement caused by others factors was between −80 and 110 mm. There was variability among different sections. The section from South Huangpi Road Station to Peoples' Square Station had the most serious settlement, reaching 110 mm. The uplift near Hengshan Road may be caused by the following: (1) excavation above the tunnel, (2) serious settlement of the station, or (3) errors in the measurement of the station settlement. In the case of large station settlement, the proposed method will not be applicable.

Shanghai Metro Line No. 2

Fig. 13 shows the predicted tunnel settlement caused by land subsidence in Shanghai Metro Line No. 2 by 2010 based on the proposed method. The spatial distribution of the tunnel settlement below the tunnel is similar to that of the ground subsidence. As the ground below the tunnel has great differential subsidence, the tunnel shows obvious longitudinal deformation.

Fig. 14 shows the tunnel settlement in Shanghai Metro Line No. 2 by 2010 caused by other factors. It can be seen that, influenced by other factors, the tunnel generally settled with a maximum magnitude of 85 mm. In the section from East Nanjing Road Station to Lujiazui Station, the tunnel experienced a significant uplift of 110 mm. This is because the tunnel was constructed at a depth of 6–7 m under the Huangpu River. During tunneling, the overlying soil was severely disturbed, leading to a decrease in shear strength. This produced a stress relaxation on the top of the tunnel. The buoyancy exceeds the weight of the tunnel and the loading of the overlying soil, leading to an uplift of the tunnel over a long

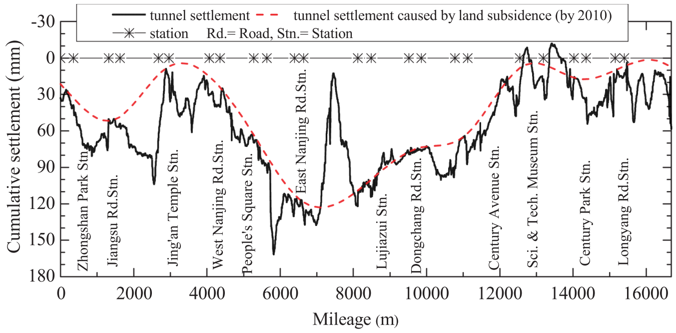

Fig. 13. Cumulative tunnel settlement of Line No. 2 caused by land subsidence

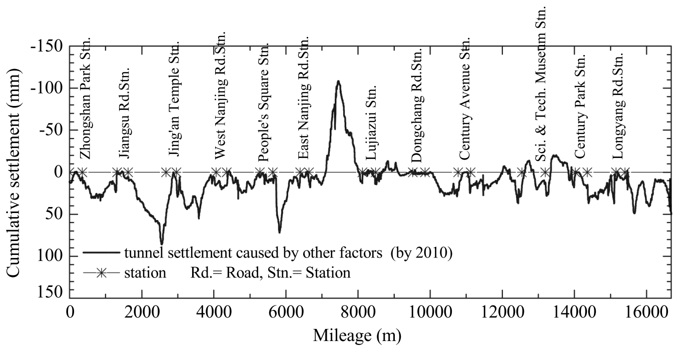

Fig. 14. Cumulative tunnel settlement of Line No. 2 caused by factors except land subsidence

period of time. The tunnel in the section between Shanghai Science and Technology Museum Station and Century Park Station experienced an uplift of about 20 mm, as shown in Fig. 13. This section is also influenced by buoyancy because it is located under a lake (Jingtian Lake) in Century Park.

Influencing Weight of Land Subsidence

Fig. 15 shows the cumulative settlement caused by land subsidence plotted against total settlement, for the maximum settlement points in each section of Metro Lines No. 1 and No. 2. It can be seen that the relationship between the two can be fitted by a straight line with a slope of 0.625. That is, the land subsidence–induced settlement accounts for 62.5% of the maximum cumulative settlement in sections of Metro Lines No. 1 and No. 2, up until 2010.

Effect of Other Factors

Fig. 16 shows the tunnel settlement caused by other factors plotted against time in the locations of P1 and P2 (referred to Fig. 12). It can be seen that the tunnel settlement caused by other factors increases with time, at a decreasing rate. After 15 years' operation, the tunnel settlement tends to converge. By 2010, the cumulative settlement caused by other factors in P1 and P2 are 93.9 and 83.8 mm, respectively.

Perspectives on Future Study

As presented previously, land subsidence has been the main factor causing the long-term settlement of Shanghai Metro Lines No. 1 and No. 2. Because countermeasures (e.g., groundwater pumping

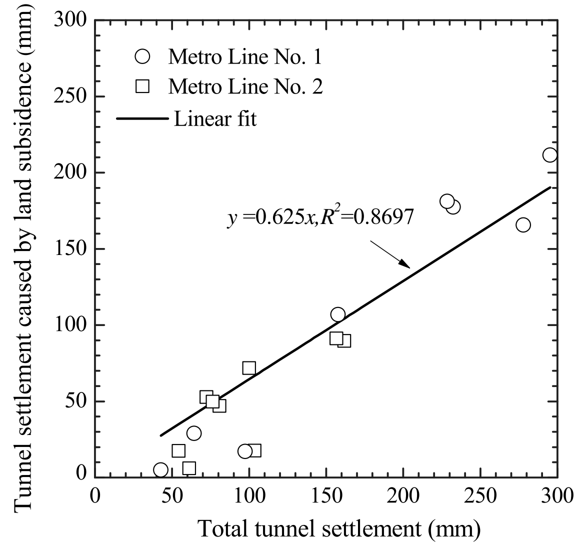

Fig. 15. Relationship between tunnel settlement caused by land subsidence and total settlement

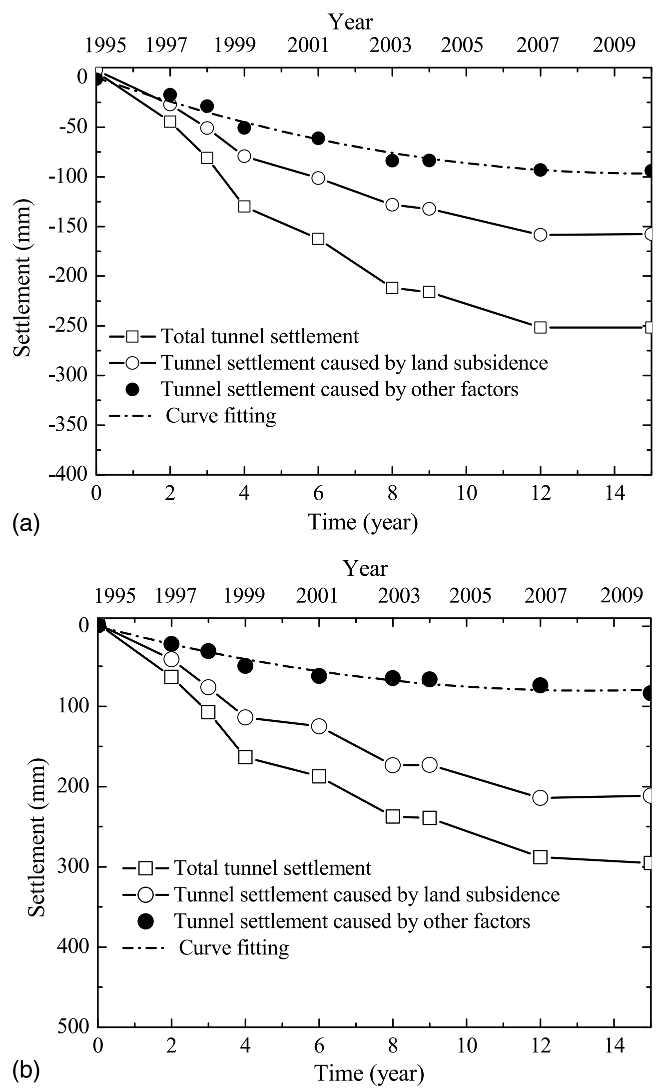

Fig. 16. Settlement varied with time due to causes except land subsidence

limitations) have been implemented in recent years, the average land subsidence has been controlled within a rate of 6 mm per year in Shanghai (SMBPL 2015). In the central urban area the ground surface has been observed to undergo rebound. However, it is still worth noting that in some suburban regions, new subsidence has developed with rates reaching 20 mm per year. Such differential land subsidence may pose a threat to the expansion of metro lines into suburban regions. The influence of the land subsidence on these new lines should be further identified using the proposed method so that countermeasures can be implemented to protect the tunnels.

Other factors have also contributed to a significant amount of the tunnel settlement according to the case studies presented in the previous context. These factors are summarized as follows: (1) reconsolidation and creep behavior of surrounding soil (Shen et al. 2015; Yin et al. 2011), (2) train running load (Wu et al. 2015a), (3) leaking-induced long-term consolidation (Shen et al. 2014, 2015), and (4) nearby construction-induced settlement (Shen et al. 2013d; Li et al. 2016; Wu et al. 2016). Shield tunneling inevitably disturbs the surrounding soils, leading to consolidation and secondary consolidation in the early operational years. The operation of trains provides a long-term repetitive, low-frequency vibration load that causes permanent plastic strain in the subsoils. According to Wu et al. (2015a), the train load–induced settlement reached about 15.5 mm in the initial 8 years, 60% of which occurred within the initial 6 months. However, the differential settlement of the tunnel may lead to distortion of the track, which may in turn increase the dynamic load of the train and cause further consolidation and settlement of the tunnel. In addition, shield tunnels commonly have leakage problems. The permeable tunnel introduces a new drainage boundary condition that leads to long-term reductions in pore water pressure and associated consolidation settlements. Besides, nearby construction, e.g., deep foundation excavation or tunneling under/over an existing tunnel, are also responsible for the long-term settlement of tunnels. These factors can easily cause a significant differential settlement in local places associated with great joint deformation. The mechanisms of these factors on tunnel settlement need to be further investigated.

Conclusions

This paper investigates the correlation between the settlement of metro tunnels and land subsidence in Shanghai, and the influence of land subsidence on tunnel settlement. The following conclusions can be drawn:

1. Comparison between the settlement of metro tunnels and land subsidence along the tunnel axis in the same periods leads to the conclusion that the tunnel settlement is correlated with sublayer subsidence rather than ground surface subsidence. To identify the tunnel settlement caused by land subsidence, sublayer subsidence needs to be obtained. However, the imperfection of the current layered monitoring system made direct measurement impractical.
2. The settlement of metro stations was found to be generally caused by local land subsidence according to the result of load transfer analysis. Based on this, the tunnel settlement caused by land subsidence can be evaluated by simply taking the stations as the monitoring point at the depth of the tunnel. The detailed steps are as follows: (1) use a Cartesian coordinate system with the longitudinal distance along the tunnel as the x axis and the settlement as the y axis; (2) plot the scatter points of the station settlements; and (3) use a cubic spline function to fit the line of the station points, and the derived fitting curve represents the ground subsidence under the tunnels.
3. Land subsidence–induced settlement accounts for 62.5% of the maximum cumulative settlement in sections of Metro Lines No. 1 and No. 2 up until 2010. Other influential factors tend to cause tunnel settlement rather than uplift, except for in those crossing below rivers. The cumulative settlement caused by other influencing factors increases with time but at a decreasing rate, and tends to converge after 15 years' operation. Compared to land subsidence, other factors are more harmful to the tunnel structure because they easily cause a significant local differential settlement associated with great joint deformation.

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