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Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai

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ABSTRACT

The Quaternary soft deposits of Shanghai form a multi-aquifer–aquitard system (MAAS) with aquitards of high compressibility and aquifers of high groundwater table. The metro tunnels in Shanghai are generally constructed at a depth of 9–15 m in a very soft clay layer with high water content, high compressibility and low permeability. According to the field monitoring results since completion of construction, significant settlement and substantial differential settlement of tunnels have occurred after more than 10 years' operations. The long-term settlement rate was greater in the first few years and afterwards reduced gradually. Non-uniform settlement was observed in the following situations: (a) under variable soil conditions; (b) between station and tunnel; (c) at cross passages and the ramp section; (d) at tunnel sections crossing below river. The long-term settlement and differential settlement of tunnels has led to serious longitudinal deformation. The deformation pattern of tunnels is step between rings rather than by beam/cylindrical shell bending. Most of the lining rings distort into the shape of a horizontal ellipse (tunnel squat) but a few acquire the shape of a vertical ellipse. Large tunnel deformation has caused groundwater infiltration and the separation of ballastless track bed and lining. Further analysis shows that long-term tunnel settlement is mainly due to urbanisation-induced land subsidence in Shanghai. The magnitude of tunnel settlement is correlated to sublayer settlement rather than ground surface settlement. In the early operational years, post-construction settlement induced by tunnelling and the cyclic loading of trains may contribute significantly to the tunnel settlement. However, at some special places, nearby construction and groundwater infiltration are responsible for the long-term settlement of tunnel.

1. Introduction

Shanghai is located on the south bank of the estuary of Yangtze River with a total land area of 6340 km^2. The majority of the land area in Shanghai involves a soft deltaic deposit with some isolated outcrops of bedrock. The bedrock outcrops are scattered in isolated mounds with a total area of about 2.5 km^2. Most of the bedrock is buried under Quaternary and Tertiary sediments at a depth of over 300 m (Xu et al., 2009, 2012a, 2013a, b). Shanghai contains 17 districts, of which 8 districts are in the main urban area. Shanghai has an ongoing process of rapid urbanisation with continuing economic development over 20 years (NBSC, 2011). According to NBSC (2011), the population of Shanghai reaches 25 million. The urban transportation system of Shanghai is thus facing increasing pressures. In order to solve the mass transportation problem, Shanghai has been building a metro system since the mid 1980s. Fig. 1 shows the distribution map of the metro system of Shanghai. At the end of June 2010, there were 11 lines and 280 stations with a total mileage of about 410 km in operation. Details of the opening year and the extent of each line are tabulated in Table 1. The average daily number of passengers is about 6 million, representing 40% of the total public transport passengers in Shanghai. By 2020, the metro system will expand to 22 lines with 877 km long according to Shanghai urban rapid rail transit plan (SAES, 2009).

The Quaternary deposit in Shanghai primarily consists of a phreatic aquifer group (Aq0) and five artesian aquifers (AqI–AqV) that are separated by six aquitards (AdI–AdVI). The phreatic aquifer group consists of a phreatic aquifer (Aq01) and a low-pressure artesian aquifer (Aq02). The details of the forming era and the sedimentary environment of each stratum can be found in several works (Xu et al., 2009; Shen et al., 2006, 2010, 2011). The soft deposits of Shanghai are characterised by a high water content, high compressibility, low permeability, and low shear strength. When these soils were disturbed, there will produce large volume

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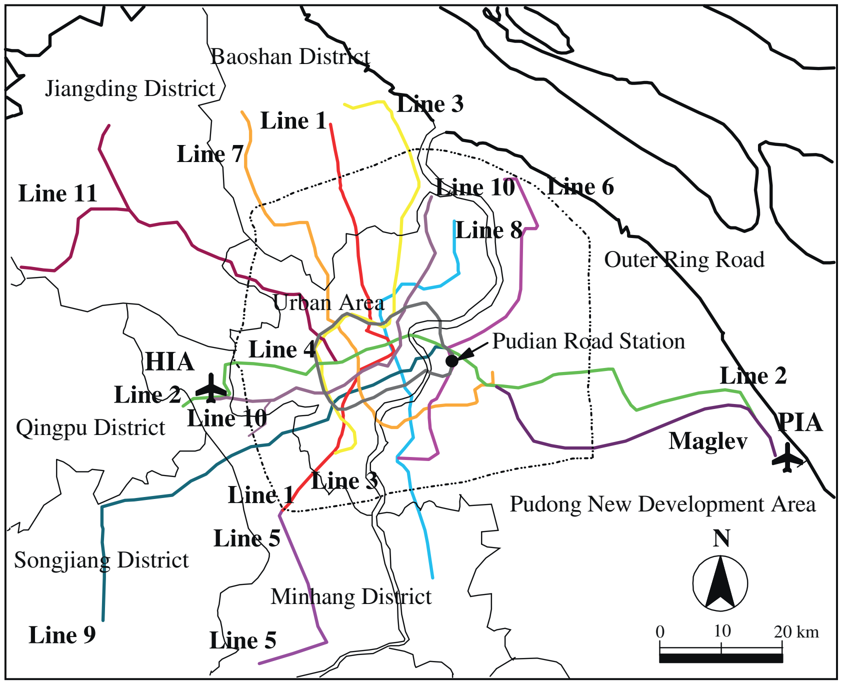

Fig. 1. Distribution of rail track system in Shanghai.

Table 1
List of the opening year and the extent of each metro line.

Line	Terminals	Opened	Length (km)	Stations
1	Fujin Road Stn.–Xinzhuang Stn.	1995	36.4	28
2	East Xujing Stn.–Pudong International Airport Stn.	1999	63.8	30
3	North Jiangyang Rd. Stn.–Shanghai South Railway Stn.	2000	40.3	29
4	Loop line starting at Yishan Road Stn.	2005	33.7	26
5	Xinzhuang Stn.–Minhang Development Zone Stn.	2003	17.2	11
6	Gangcheng Road Stn.–South Lingyan Rd. Stn.	2007	31.1	27
7	Meilan Lake Stn.–Huamu Rd. Stn.	2009	44.2	30
8	Shiguang Rd. Stn.–Aerospace Museum Stn.	2007	37.5	28
9	Songjiang Xincheng Stn.–Middle Yanggao Rd. Stn.	2007	45.2	23
10	New Jiangwan Town Stn.–Hongqiao Railway Stn./Hangzhong Rd. Stn.	2010	35.4	31
11	North Jiading/Anting Stn.–Jiangsu Rd. Stn.	2009	45.8	19
	Total		410	273

Note: Rd. = Road, Stn. = Station.

changes that continue for a long time (Yin and Chang, 2009; Yin et al., 2010, 2011; Tan and Wei, 2012; Tan and Wang, in press-a, in press-b). The metro tunnels built in this soft deposit suffers from settlement and deformation-related groundwater infiltration as other similar deposits (O'Reilly et al., 1991; Mair and Taylor, 1997; Chai et al., 2004; Mair, 2008). Obviously, this may damage the structure of tunnels. Thus, control of long-term settlement of metro tunnels in Shanghai is important from all points of view.

Previous studies primarily dealt with the ground movement due to tunnelling (Shen et al., 2009, 2010). A few studies involved the mechanism of longitudinal deformation (Liao et al., 2008). However, reports on long-term settlement of shield tunnels in soft ground are rare. The objectives of this paper are: (i) to present the long-term deformation behaviour of the metro tunnels, and (ii) to interpret the mechanism of the long-term settlement with the relationship to the geotechnical properties.

2. Geological and geotechnical conditions

The soft deposits of Shanghai were formed during the Pleistocene and Holocene epochs under the influence of several transgressions and the scouring of the Yangtze River (Xu et al., 2009, 2012a,b; Shen and Xu, 2011). Fig. 2 illustrates the geological formation, soil types, and hydrogeology of the upper 70 m deposit, which is the greatest depth reached by anthropic construction activities. As shown in Fig. 2, the deposit is a multi-aquifer–aquitard system (MAAS), in which clayey soil and sandy soil overlap (Xu et al., 2009, 2012a,b; Shen and Xu, 2011). According to the Standard of Geotechnical Investigation of Shanghai (CCEMS, 2012), the deposit up to a depth of 70 m contains 9 geotechnical soil layers following the soil properties and grain size distribution (labelled in circled numbers from ① to ⑨ in Fig. 2). Each soil layer is further divided into sublayers based on the colour of soil. The buried depth of each layer varies with the location (CCEMS, 2012).

The geological and hydrogeological formation of each layer from the ground surface to 70 m depth is described as follows. The upper deposit is a clayey soil layer. Next is a sand layer (the first sand layer), which is a phreatic aquifer, where the groundwater level is 0.5–2.5 m below the surface. Underlying the first sand layer, is the first stiff soil layer, which is distributed in the Qingpu District. The following layer is the first soft clay with a high clay (particle size less than 5 μm) content in a saturated and plastic