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Laboratory model tests and field investigations of EPB shield machine tunnelling in soft ground in Shanghai

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ABSTRACT

In the last decades, many studies have been presented by different scholars on the environmental problems induced by the shield tunnelling in soft ground. But it mainly concentrated on ground surface settlement, tunnel surface stability and the influence to existing structures. Among them, little attention was paid to soil disturbance caused by the mismatch of machine's operation parameters. In order to reveal this inherent relation, a series of laboratory model tests were carried out in the 1/16 scale for a field tunnel in practice where the tunnel had 6.4 m diameter. The tests to simulate earth pressure balance (EPB) shield tunnelling in soft ground were conducted with a microshield machine (0.4 m diameter). Measurements were carried out simultaneously in each test for total jack thrust force, cutting torque, chamber pressure, mucking ratio, ground surface displacement, and earth pressure. Based on the analysis of test results under different overburden ratio, cutterhead aperture ratio and screw rotation speed, the relationships between machine's operation parameters themselves and its influence on disturbance to surrounding soil mass were discovered. Such discoveries were also verified by the field investigations. These results are useful for engineers and technicians to select suitable and serviceable machine operation parameters and reduce environmental influence at all stages of tunnel construction.

1. Introduction

In order to resolve the problems of increasing traffic congestion, reduced surface vacancy and huge pedestrian volume, Shanghai's city planners are becoming more interested in using the underground space. According to the overall plan of Shanghai city, there are 21 lines planed in the urban rail transit network. Among them, 16 lines are subway tunnels which are all constructed with shield tunnelling method. Since Shanghai is located in the eastern coast of China, thick layer of soft clay is wildly distributed in the underground of it. When shield tunnelling in such soft ground, it will inevitably perturb the surrounding soil. Therefore, it is necessary to have a comprehensive understanding on the tunnelling induced problems. Practically, such problems may not be solved completely by theoretical research, but through field investigations and model tests sometimes.

Based on the field investigation data, great progress in calculating surface settlement or lining stresses had been made in the past few decades (e.g. Peck, 1969; Rowe and Kack, 1983; Harris et al., 1994; Nakamura et al., 2003; Maeda and Kushiyama, 2005; Migliazza et al., 2009, etc.). But due to time consuming and cost expensive, the instrumented projects and field investigations are limited sometimes. For these reasons, the reduced physical model test has been an effective and economical way in studying the shield tunnelling problems.

Physical modeling is concerned with replicating a process or a phenomenon in a reduced scale version of the prototype (Viswanadham, 2005). Recently, many tests have been conducted under 1g conditions or in a centrifuge to investigate the shield tunnelling behavior in soil (Meguid et al., 2008). For example, in order to verify the performance of the excavation mechanism of the DPLEX shield method, cutting face support, etc., an experimental shield having rectangular cross section was fabricated to excavate artificial grounds of fine sand, compacted sand, gravel, and gravel with cobbles. In the tests, the machine's operation parameters were taken into account to keep the balance state of cutting face. But the relationship between the operation parameters was not investigated (Kashima et al., 1996). Nomoto et al. (1999) developed a 100 mm diameter miniature tunnel boring machine to simulate the complete process of shield tunnel construction from cutting to tail void formation in centrifuge. In his tests, only earth pressure around the tunnel and ground surface displacement were monitored and analyzed. Sharma et al. (2001) used polystyrene foam to be dissolved by organic solvent to simulate the progressive tunnel face advance and the gap of shield tail in a centrifuge. In

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that test, the development of settlement trough was reproduced, but no model shield was used. Sterpi and Cividini (2004) conducted laboratory model tests to investigate the behavior up to failure of shallow tunnels excavated with EPB shield machine in strain softening cohesionless media. The tunnelling works were simulated through the gradual reduction of the air bag pressure, until failure of its face occurs. Lee and Bassett (2007) carried out two dimensional laboratory model test for the pile–soil-tunnelling interaction. The model tunnel device can reduce its diameter to simulate volume loss.

As can be seen, a lot of research works on the shield tunnelling problems have been done by many pioneers, but it mainly concentrated on ground surface settlement, redistribution of soil stress, tunnel surface stability and the influence to existing structures. Among them, little attention was paid to the soil disturbance caused by the mismatch of machine's operation parameters. Therefore, in order to reveal this inherent relation, the interval tunnel from Siping Road station to Quyang Road station of Shanghai Metro Line 8 was taken as reference prototype, then a series of laboratory model tests and field investigations were carried out accordingly. Based on the analysis of test results and field investigation data, some useful conclusions can be drawn.

2. Project overview

2.1. Engineering background

Shanghai Metro Line M8 lies in the city central area. It crosses through six districts totally, i.e. Yangpu, Hongkou, Zhabei, Huangpu, Luwan District and Pudong New Area. Along the tunnel alignment, there are many residential areas. Therefore, the tunnel will have to pass beneath the urban areas with heavy traffic or dense underground pipelines as well as crowded building groups. The tunnel longitudinal gradient is in humped type or single slope type with maximum gradient of 3%, and the buried depth of tunnel axis is mainly from 7.06 to 31.125 m.

The interval tunnel from Siping Road station to Quyang Road station is located in Yangpu district. It is an important part of Shanghai Rail Transit. As shown in Fig. 1, the interval tunnel starts from Siping Road station along West Dalian Road to Quyang Road station, about 870 m long, with its mileage from AK11 + 090 to AK11 + 960. The tunnel having outer diameter of 6.4 m is constructed with EPB shield machine. The elevation at tunnel bottom is from −16.0 or so to −11.0 m. During the construction, the shield machine mainly works under West Dalian Road.

2.2. Site location and topography

Along West Dalian Road, there are dense residential areas, such as Yangpu Primary School, Hongwei Middle School, Yutian Village, Dalian Village, and Honglian Building. Most of them are multi-storey buildings, except that Honglian Building and Quyang residential area are high-rise buildings. Along the tunnel line, the ground surface level is about +3.57 to +3.99 m. Generally, the working site belongs to coastal plain landform type topography.

2.3. Soil composition and characteristics

As revealed by engineering geological investigation report, the stratum from surface to 40.45 m deep can be divided into six layers in terms of its genetic type. Among them, layer ② and layer ⑦ can be further divided into several sublayers according to the engineering properties. In the proposed interval, the average ground surface elevation is +3.70 m; the elevation of tunnel floor is −10.789 to −17.236 m. The embedded depth of tunnel floor presents the trend of large in the middle and small at two ends, as shown in Fig. 2.

As the stratum was cut by ancient river firstly, and then the grey silt of littoral-estuarine facies deposited, such as layer ②$_{3-1}$ and layer ②$_{3-2}$, which leads to the miss of grey silty clay, i.e. layer ③. But the other layers under layer ④ distribute evenly.

The characteristics of the different soil layers are described as below.

Layer ① is miscellaneous fill, about 1.0–2.3 m thick. The superficial coat of this layer is mainly concrete floor, under which is the ballast mixed with few cohesive soil. In the central, the main component is rock block and broken brick mixed with cohesive soil. In the lower part, it is mainly filled with cohesive soil mingled with scree and cinder.

Layer ②$_1$ is brown to grey yellow silty clay. The layer surface elevation is 1.46–2.75 m, generally 2.1 m. It is thin, with mean value of 1.2 m.

Layer ②$_{3-1}$ is grey clayey silt mixed with cohesive soil. It is slightly dense. The layer surface elevation is 0.47–1.29 m, generally 0.9 m. The thickness varies greatly from 1.1 to 10.1 m, generally 4.9 m. Its specific penetration resistance (P_s) is about 1.72–2.77 MPa and the standard penetration numbers (N) is about 3–7.

Layer ②$_{3-2}$ is grey sandy silt, slightly dense to middle dense. The layer surface fluctuates obviously, and its elevation varies from −9.45 m to −0.32 m, generally −4.0 m. The layer thickness is from 2.8 to 11.8 m, generally 7.5 m. Its P_s value is about 3.60–7.74 MPa and the N value is about 3–14.

Layer ④ is grey silt clay. Its surface elevation is about −13.38 to −8.92 m, generally −10.7 m. The layer is about 4.0 m thick and its P_s value is 0.72–0.78 MPa.

Layer ⑤$_1$ is grey silty clay, soft plastic. It distributes throughout the entire tunnel interval. The layer surface elevation is about −15.55 to −13.08 m, generally −14.6 m. Its thickness is about 5.40–7.75 m, generally 6.5 m.

Layer ⑥ is silty clay, dark green to grey yellow, evenly distributed. The surface elevation is −21.88 to −20.35 m, normally −21 m and the thickness is about 3.20–5.30 m, generally 4.3 m. Its P_s value is about 2.05–2.71 MPa.

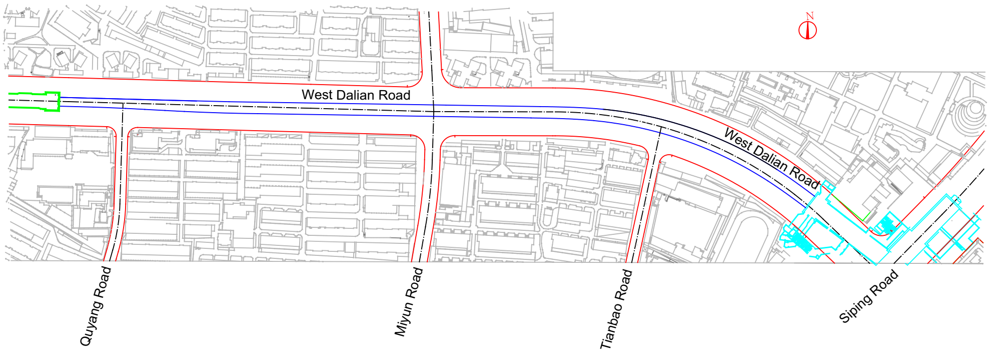

Fig. 1. Plan layout of the interval tunnel.