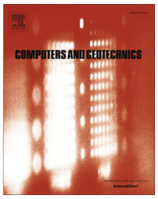
Computers and Geotechnics 56 (2014) 121–132

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo



Geotechnical influence on existing subway tunnels induced by multiline tunneling in Shanghai soft soil

Zhiguo Zhang [a,b,c,*], Maosong Huang [b,d]

[a] School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China
[b] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China
[c] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China
[d] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 19 August 2013
Received in revised form 14 November 2013
Accepted 28 November 2013
Available online 15 December 2013

Keywords:
EPB shield
Multiline tunneling
Geotechnical deformation
Simplified analysis
Numerical simulation
Case history

ABSTRACT

Multiline tunneling construction in soft soil significantly impedes risk control and environmental protection. Current research has investigated on the effect of single-line shield excavation on surrounding environments and tunneling for parallel-crossing or perpendicular down-crossing underground structures. However, minimal attention has been given to soil disturbances induced by multiline tunneling and complex overlapped interaction mechanics for adjacent structures, such as existing above-crossing and down-crossing subway tunnels. Few studies focus on oblique crossing construction and setting rules for the operation parameters of shield machines. Based on the Shanghai Railway transportation project and in situ monitoring data, the deformation analyses of existing subway tunnels induced by an earth pressure balance (EPB) shield during the process of above-overlapped and down-overlapped crossing tunnels with oblique angles are presented. The deformation analyses employ the three-dimensional finite element (3D FE) numerical simulation method, and the simplified analytical method. The analysis results from the theoretical methods are consistent with the monitoring data. The setting rules of multiline propulsion main parameters, including the earth pressure for cutting open, and the synchronized grouting, are also established. This study may provide a theoretical basis for the development of properly overlapped crossing schemes and geotechnical protective measures during multiline tunneling construction in soft soil.

1. Introduction

Rapid economic development and urbanization in China has substantially accelerated land utilization; as a result, city planners are becoming more interested in the use of underground space to construct transportation infrastructures and facilities. Recently, complicated urban railway transportation systems, which serve as a 3D framework for underground space utilization, have been planned in cities such as Beijing, Shanghai, Nanjing, and Shenzhen. This ambitious plan is currently being implemented in high-speed construction [1–5]. In Shanghai, 11 metro lines with a total length of 420 km have been completed. By the end of 2020, 22 metro lines comprising a total length of 880 km will be operational; the majority of the lines are being constructed using the shield tunneling method.

Shield tunneling technology has been extensively applied to urban underground spaces due to advantages such as high speeds, a strong safety record, and minor disturbances to surface traffic. However, the underground structures of piles, municipal pipelines, and subway tunnels have hindered the use of potential construction space for new tunnels. Shield tunneling frequently overlaps and bypasses existing structures. Significant construction risks and potential safety hazards are encountered during complex overlapped construction. Because Shanghai is located in the Yangtze River Basin, a thick layer of soft clay is distributed throughout the underground space. Overlapped tunneling in soft ground will inevitably perturb the surrounding soil, which may induce adverse effects on adjacent structures (e.g., cracks in buildings and reductions in pipeline and service tunnel capacities). Therefore, a comprehensive understanding of the deformation behavior of adjacent metro tunnels induced by overlapped tunneling is critical. Theoretically, the response of existing tunnels to adjacent construction is problematic due to the interaction between soil disturbance induced by tunneling and the bearing capacity of existing tunnels. This problem has been examined in recent years using a variety of approaches: field observation, physical model testing and finite element numerical simulation.

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[*] Corresponding author at: School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China.
E-mail address: zgzhang@usst.edu.cn (Z. Zhang).

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http://dx.doi.org/10.1016/j.compgeo.2013.11.008

Based on field investigation data, significant progress in the calculation of ground surface settlements or lining stresses induced by tunneling has been made over the past few decades [6–13]. Field observations of the interactions between closely spaced crossing tunnels on the Jubilee Line Extension in London were conducted by Kimmance et al. [14]. Asano et al. [15] proposed an observational excavation control method for a mountain tunnel that was excavated adjacent to an existing tunnel. Li and Yuan [16] presented displacements of an existing tunnel caused by undercrossing tunnels in different undercrossing stages using an automatic high-performance total station measuring system. Field observations remain the most prevalent and recognized approach for understanding the interaction behavior between adjacent and crossing tunnels.

Numerous attempts have been made to develop physical model tests, including scale model tests and centrifuge model tests, to investigate the influence of tunneling on adjacent tunnels, such as twin parallel tunnel engineering. Adachi et al. [17] used scale model tests to analyze the interaction behavior between double-line tunnels. Kim [18,19] performed scale model tests to investigate the influence of tunnel proximity and alignment and liner stiffness on the interactions between closely spaced tunnels in clay. Vorster et al. [20] discussed the underlying mechanisms governing pipeline response to tunneling based on centrifuge model tests. Lee et al. [21] performed a series of centrifuge model tests to investigate tunnel stability and arching effects during single-line and double-line tunneling in soft clay soil. Byun et al. [22] conducted several large-scale model tests to estimate the ground behavior around tunnel-crossing zones and tunnel behavior for tunnels located above newly excavated tunnels.

In addition, finite element numerical simulation is an effective method to analyze the deformation behavior of adjacent tunnels induced by tunneling. It considers the nonlinear interaction between existing tunnels and surrounding soils, soil elasto-plastic behavior, the freedom for the tunnel to heave, and the complexity of construction operations. Addenbrooke and Potts [23,24] used a 2D finite element method to analyze ground movements and lining behavior induced by twin tunnel construction. Chapman et al. [25] conducted a series of 2D finite element analyses to study the settlements above the closely spaced multiple tunnel construction of the London Clay. Ng et al. [26] reported multiple interactions between large parallel twin tunnels that were constructed with stiff clay using the 3D finite element method. Chehade and Shahrour [27] presented a 2D finite element numerical model for the optimization of the relative position of twin-tunnels and the construction procedure.

Previous studies have primarily focused on the tunneling case of parallel-crossing or perpendicular down-crossing underground structures. However, minimal attention is given to multiline overlapped tunneling engineering, such as existing above-crossing and down-crossing subway tunnels. Case histories of oblique crossings are rarely reported in the literature. Numerical simulation is a common analysis technique. No research on special overlapped interactions using a simplified theoretical method has been reported. The problem of tunnel construction using multiline crossing with an oblique angle is becoming increasingly important in urban areas where available underground space is limited. Because the total cost of the construction of deep transport tunnels in urban areas is generally greater than the construction of shallow tunnels, a tunnel route that is located closer to existing underground structures is generally financially preferable. Thus, there has been considerable interest in recent years for the development of analysis theories and field measurement techniques for the investigation of the tunnel interaction problem.

This research presents a tunneling case of the second-stage north route of Shanghai Railway transportation line 11 to study the deformation behavior of the subway tunnel in service, which is induced by an EPB shield in soft clay during above-traversing and down-traversing processes. Various research approaches, including the simplified theoretical method, and 3D FE numerical simulation method, are performed to investigate the influence of multiline overlapped tunneling on existing tunnels. The simplified theoretical method is derived from the Winkler foundation. The longitudinal settlement equation for above-overlapped and down-overlapped construction of existing tunnels is obtained. The 3D numerical simulation method enables the optimization of the construction scheme and shield excavation parameters. The study cases of above-overlapped and down-overlapped crossings with large oblique angles are analyzed. The setting rules of shield tunneling parameters, including earth pressure for cutting open, and synchronized grouting are established based on the monitoring data. The proposed methods provide a theoretical basis for the development of proper protective measures for subway tunnels in service during tunneling excavation and the overlap traversing process. The research results provide shield propulsion references for the future construction of similar projects, such as multiline passing through existing structures.

2. Engineering background

Shanghai Railway transportation line 11, which is one of the main components of the municipal transportation network, is located in the downtown area of Shanghai. Metro line 11 runs in a north–south direction and transports an extremely large number of passengers daily. The second-stage of the north route of line 11 passes through four districts: Changning, Xujiahui, Pudong New Area and Nanhui. It comprises a total length of 20.89 km and thirteen stations and extends from Huashan Road to Luoshan Road. As shown in Fig. 1, the transit tunnel from Xujiahui station to Shanghai Gymnasium station (Section No. 11.G.8) is a critical part of the second-stage of the north route of line 11. Existing line 1 and line 4 are encountered in the excavation site. The case of multiline overlapped tunneling discussed in this study is located between the Oriental Golden Horse building and the park under Lingling Road, in which the sport cultural center is located, as shown in Fig. 2. This transit tunnel is outfitted with two earth pressure balance shield machines. The shield tunneling machine is a mudding earth pressure balance-type machine with an outside diameter of 6.43 m. The up-line and down-line shields begin from the south shaft of Xujiahui station in a successive manner and subsequently propel to Shanghai gymnasium station from north to south. The up-line shield, which takes the lead out of the hole, covers a distance of approximately 100 rings with the down-line shield. When the up-line and down-line shields pass through Lingling Road, the shield of line 11 will obliquely cross the service tunnel of line 4 at a 75° angle.

The sectional view of the position relationship between the shield of line 11 and the existing tunnel of line 4 is shown in Fig. 3. It should be noted that this material for the bottom layer extends indefinitely. The up-line shield crosses below line 4 and the minimum clear distance between the up-line shield and line 4 is 1.82 m; the down-line shield crosses above line 4 and the minimum clear distance between the down-line shield and line 4 is 1.69 m. The figure also shows that the covering soil depth of the down-line tunnel is approximately 6 m. The tunnel lining, which is a universal ring wedge segment, is composed of concrete. The outside diameter of the segment is 6.2 m and the inner diameter of the segment is 5.5 m. The ring width is 1.2 m and the segment thickness is 0.35 m. The segment concrete strength is classified as grade C55 and the concrete impermeability is classified as grade S12. The full circumference straight-joint assembly process is