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Three-dimensional finite-element analysis on ground responses during twin-tunnel construction using the URUP method

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ABSTRACT

The paper presents a finite-element analysis of a metro tunnel project using the URUP method in which the shield machine is launched and received at the ground surface level. During the tunnelling process, the cover depth varied from 0.7D (D is the excavation diameter) to −0.3D in which case the shield machine was partially above the ground surface. A three-dimensional finite element model is proposed via the commercial software ABAQUS considering the actual geological condition and tunnelling procedures. Elasto-plasticity constitutive models are utilised for the top three strata in the finite element analysis (FEA). Constant gradients corresponding to material density are assumed for the face supporting pressure and the grouting pressure in the model. The ground contraction method is employed to simulate the shield-induced volume loss. The numerical model is firstly validated against the field measurement data considering the surface settlement. Parametric studies are performed subsequently to investigate the influence of some key tunnelling variables including cover-to-diameter ratio and face supporting pressure on the ground responses. According to the FEA, a critical cover depth of 0.55D is proposed for URUP method below which value instability and collapse of surrounding soils will be highly likely.

1. Introduction

As documented in various tunnelling cases, TBM (Tunnel Boring Machine) has become the prevalent choice for tunnelling activities in congested urban areas due to its safe working environment and small disturbance to surrounding ground (Fargnoli et al., 2013, 2015; Liu et al., 2014; Standing and Selemetas, 2013; Wongsaroj et al., 2007). As a predominant style of the mechanised tunnelling method, TBM tunnelling method also owns the merit of largely reducing the excavation volume in comparison to traditional tunnelling approaches, e.g. the open-cut tunnelling method. Nevertheless, launching and receiving shafts still need to be excavated prior to the initiation of conventional TBM tunnelling, which restricts the application of TBM tunnelling in cases with extremely narrow construction space. In order to shorten the construction period and minimise the tunnelling impact, the URUP (Ultra Rapid Under Pass) method was developed in Japan in 2006 (Hayashi et al., 2006; Izawa et al., 2006) and adopted thereafter in multiple tunnelling projects of Oi Area (Fujiki et al., 2009; Nakamura and Hazama, 2010; Zick et al., 2013). As shown in Fig. 1, when this method is used, TBM is directly driven into and out of the ground without the need of working shafts (Zhang et al., 2013). This new approach is normally associated with Earth Pressure Balanced (EPB) TBM as the excavation face may be exposed to the atmosphere. Since in the URUP method TBM is normally super-shallowly buried or sometimes even partially above the ground surface, the control of face supporting pressure and grouting pressure during TBM driving is of extreme importance (Nakamura and Hazama, 2010). Two projects in the western part of the Netherlands (i.e. an underpass at Goes and the Rijnlandroute tunnel, respectively) were used to demonstrate the feasibility of the URUP method (Beijer, 2010; Oldenhave, 2014). According to these two case studies, the URUP method is a reasonable option for the construction of both underpass and large diameter tunnel in the western part of the Netherlands, despite that it is economically not competitive compared to the conventional TBM tunnelling approach.

The underground space has been massively exploited in Eastern China to meet the increasing demand for underground space and transportation in urban areas (Lin et al., 2015; Liu et al., 2014; Min et al., 2015; Ng et al., 2013; Shen et al., 2014; Xu et al., 2015; Zhang and Huang, 2014). The densely-distributed underground and overground infrastructure systems greatly squeeze the construction space and require rigorous ground movement

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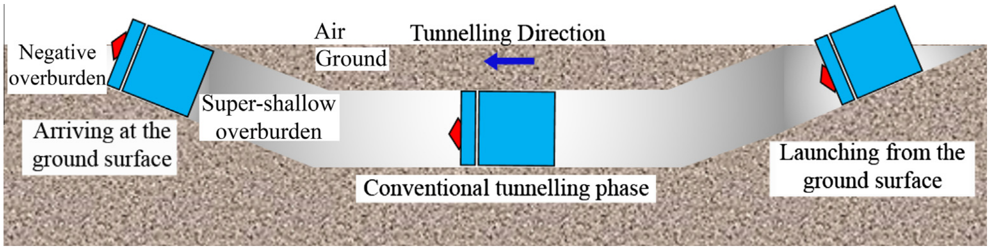

Fig. 1. Sketch illustrating the URUP tunnelling process (Zhang et al., 2013).

control. Thus, the URUP method becomes a reasonable solution for tunnelling projects under such conditions. Since there is no prior experience of URUP tunnelling in China, a full-scale test using the URUP method was conducted to excavate the twin tunnels between the Moling Station and Jiangjun Ave. Station of the Nanjing Metro Line S1 (NMS1) in China. Comprehensive monitoring programme was designed to investigate ground responses due to UPUP tunnelling work.

The paper presents the results of a three-dimensional finite element analysis (FEA) on the aforementioned full-scale test performed in Nanjing, aiming at evaluating the influence of multiple tunnelling variables on the ground responses by comparing the FEA results with the field measurement data.

2. Project overview and geotechnical conditions

2.1. URUP tunnelling section of Nanjing Metro Line S1

The URUP section investigated in this study is a part of Metro Line S1 of Nanjing, which is the capital of Jiangsu Province located in the eastern part of China. The URUP tunnelling section has a total length of 123.7 m along its eastbound direction and 124.6 m in the westbound direction respectively (Fig. 2). In this section, two twin tunnels spaced by 8.5 m between the central axes were excavated using an EPB shield 7.4 m in length and 2×10^5 kg in weight. The outer diameters of the cutter head and shield body are 6.38 m and 6.34 m respectively. The designed maximum thrust force of the shield machine is 33,396 kN. Four grout injection openings are circumferentially aligned at the shield tail with an interval angle of 90°. Single-layered lining is employed with the outer and inner diameters of 6.2 m and 5.5 m, respectively. Each lining ring is fabricated from precast concrete segments which have a width of 1.2 m and a thickness of 0.35 m.

The shield machine was launched from the entrance pit and driven along the eastbound route on June 26, 2012; it reached the shield audit on October 10, 2012. The westbound tunnelling was commenced on November 11, 2012 and completed on December 30, 2012. The TBM was advanced towards the shield audit along the eastbound direction with an up-gradient of 2.8%, while it was driven along the westbound direction with a down-gradient of −2.8%. Marginal/negative cover depths were encountered during the tunnelling along the both routes (Fig. 3). Negative cover depth herein refers to the case when part of the TBM is over the ground

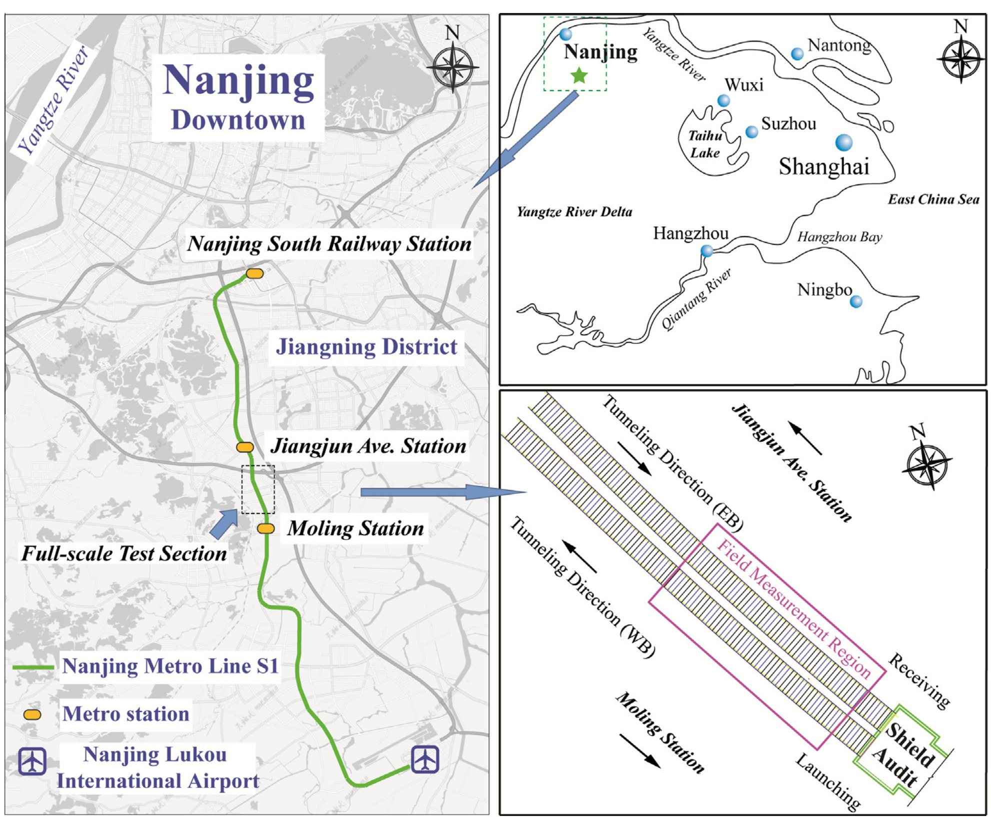

Fig. 2. Overview of the project (MAPWORLD: http://en.tianditu.com/map/index.html; annotations made by the authors).