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Studies on ground settlement and pre-arching stress of pre-cutting tunnelling method

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ABSTRACT

According to Rabcewicz (1964, 1965), tunnels should be driven full face whenever possible. The pre-cutting method is a popular tunnelling method based on this idea. This method allows safe excavation even in poor ground conditions by creating continuous pre-arching around tunnel periphery in advance. Because of high costs and safety risk in field test, the previous studies on pre-cutting method are limited and qualitative, which mainly focused on its machine, construction procedure and applicable conditions. To further develop this method, systematic and quantitative studies on ground settlement and pre-arching stress caused by it are needed. In this study, a 1:10 geo-mechanical physical model test was performed to understand the mechanism of pre-cutting method by simulating its construction process. The ground settlement, earth pressure and pre-arching stress during tunnelling were investigated. Afterwards, three-dimensional numerical simulations were performed to simulate the process of physical model test so as to compare with experimental results. The effects of different pre-cutting parameters such as length, thickness, lap length and sequence of cutting slots, which can't be sufficiently covered by the model test, were studied by numerical method. Comparative studies between pre-cutting and New Austrian Tunnelling Method (NATM) under the same geological conditions were also carried out. In general, the comparative analysis shows that the physical model test has achieved satisfactory results and the pre-cutting method has a great advantage in controlling ground deformation compared with NATM.

1. Introduction

With rapid development of high-speed railway and urban rail transit systems, there is an urgent demand for improving mechanization level of soft ground tunneling. Pre-cutting method is a unique construction technique applied in soft ground and complex surrounding environment. It was firstly introduced in the mining industry in 1950 (Van Walsum, 1991) and rediscovered in France in the seventies as 'Pre-decoupage' technique for transportation tunnels (Guilloux, 1986). The incomplete statistics show that France and Italy have built about 30 tunnels using this technique in the 1980s–1990s. According to Rabcewicz (1964, 1965), tunnels should be driven full face whenever possible. The pre-cutting method is a popular tunnelling method based on this idea. It involves the filling of a pre-cut slot with shotcrete, forming a sufficiently strong roof shell before full face excavation to provide protection during excavation. Advantages of this method include the followings: (1) Ground settlement is small for shallow tunnels, as pre-cutting followed by immediate filling causes no decompression. (2) If the machine is positioned accurately, over-excavations can be avoided, reducing workload and concrete dosages. (3) Under the protection of pre-arching, full face excavation can be carried out in places where other methods are limited to smaller headings, which speeds up construction schedule and assures the safety of workers.

Because of its unique role in reducing settlement, the construction technique and application condition were discussed by many researchers such as Eisenstein and Ezzeldine (1992), Bengt and Stillborg (1979), Peila et al. (1995), Pagliacci (1993) and Johnson et al. (1983). The method cannot, of course, be used in all ground conditions, but its application scope is now quite wide and it helps to lessen the difficulty of building tunnels in soft ground. So, it has received much concern nowadays. A new analytical method based on the convergence confinement approach to the design of pre-cutting lining was presented by Peila et al. (1995). Tonon et al. (2005) and Tonon (2009) showed the idea of building the final load-bearing structural lining ahead of a tunnel face by pre-tunnel method, which can be considered as an evolution of the pre-cutting method. Pre-cutting method and construction sequences along with the influence of some parameters were analyzed using numerical methods by Sadaghiani and Ebrahimi (2006).

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Sadaghiani and Dadizadeh (2010) also studied a new construction method for a large span metro station, which included a pre-supporting system called Concrete Arch Pre-Supporting System.

Although some previous studies about pre-cutting method have been carried out, most focus on machine, construction method and applicable conditions. For further development of this method, systematic and quantitative studies on ground settlement and pre-arching stress are necessary.

Model testing and numerical simulation are the main research methods for studying geotechnical and underground engineering problems. Geo-mechanical physical model results are more intuitive, and one can easily understand the overall mechanical characteristics of the rock masses, and their variation trend and stability conditions. Numerical simulation is economic, convenient and fast, which has quickly become the dominant method for studying engineering problems. In recent years, the method of physical model test validated by numerical simulation has been promoted and developed by researchers. Lee and Bassett (2007) focused on two dimensional laboratory model test for the pile-soil-tunnelling interaction using a close range photogrammetric technique and numerical analysis. The model test results found to be in good agreement with the finite element analysis. Shin et al. (2008) performed a large scale model testing for the pipe-reinforced tunnel heading in a granular soil to understand reinforcing mechanism and improve design practice. Supplemental numerical analyses were carried out to investigate the effect of pipe length which cannot be covered by the model tests. Zhu et al. (2010) conducted large-scale 3D geo-mechanical model tests, in which a series of experimental techniques were developed, and 3-D numerical analyses were performed to simulate the testing procedures. Lei et al. (2015) performed a 3D model test to investigate the failure mechanisms and lining stress characteristics of shallow buried tunnels under unsymmetrical loading and the results were also verified by a series of numerical simulations. Zhang et al. (2016) developed multiple deformation measurement techniques while conducting a large-scale 3D physical model test, afterwards a nodal-based Discontinuous Deformation Analysis (NDDA) method was applied to simulate the whole process of the physical model test, and achieved satisfactory results by both methods.

In this paper, a 1:10 geo-mechanical physical model test was performed to simulate pre-cutting construction process indoors. The behavior of ground and pre-arching were investigated during tunnelling. To get a comprehensive understanding of this method, 3-D numerical simulations were employed to study effects of pre-arching length, thickness, lap length, invert and sequence of cutting slots. Besides, comparisons between pre-cutting method and NATM under the same geological conditions were also investigated.

2. Construction method

The basic idea of pre-cutting tunnelling method is cutting a slot along the periphery of the tunnel to a depth prior to general tunnel construction, and the thickness of this slot can be varied depending on ground conditions. The slot creates better conditions for the subsequent excavation of the tunnel from the point of view of efficiency, safety and costs. In soft ground, it is often about 7.5–30 cm thick and 3–12 m deep, and filled with shotcrete quickly so as to form a pre-arching which providing a sufficiently strong protection before the main excavation. It should be noted that pre-arching rings are overlapped with each other for about 0.5–1 m, as shown in Fig. 1, which ensures tight connection between adjacent rings. In some cases, temporary steel arches are needed to withstand any asymmetric pressure that may be developed.

Fig. 2 shows the construction process of pre-cutting method in soft ground. The first step is cutting slots, as shown in Fig. 2(a). Cutting slots on site is demonstrated in Fig. 3. It is followed by immediate filling of concrete, forming a continuous concrete arch shell, which is usually described as pre-arching. When concrete strength reaches 8–10 MPa

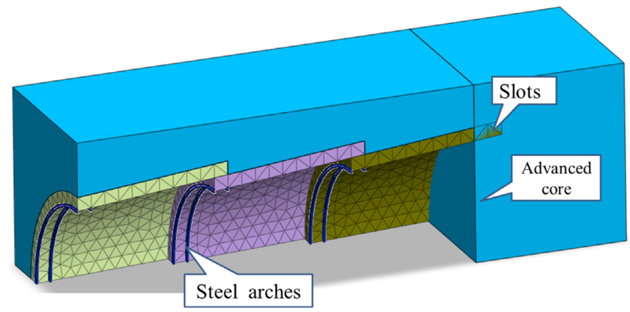

Fig. 1. Schematic view of pre-archings.

which usually takes 4–8 h, large-scale excavation of advanced core can be carried out. If needed, temporary steel arches can be erected to reinforce the pre-arching (Bougard, 1988; Walsum, 1991; Saveur and Grantz, 1997). The invert should be constructed timely to make pre-arching closed. The advance of invert is usually about 1.5 times of tunnel diameter in soft ground. Secondary lining is needed sometimes if large deformation of pre-arching occurs (Lunardi, 1997, 2000, 2008).

3. Model preparation and test procedure

3.1. Configuration

The test was carried out in a three dimensional model box located at Tunnel Construction Simulation Laboratory of Beijing Jiaotong University, as shown in Fig. 4. The length, width and height of the model box are 2.6 × 1 × 2 (m) respectively, as shown in Fig. 5. Considering its dimensions and boundary conditions, the tunnel section, as depicted in Fig. 6, with geometric scale of 1:10 was adopted in model test.

3.2. Model material preparation

(1) Model ground material preparation

The model ground was prepared to simulate typical strata in Beijing. According to geological survey and analysis of Beijing strata (Wang et al., 2008), the typical strata of Beijing are miscellaneous fill, silt, silty clay, silty sand and pebble. The strata of Beijing subway are mainly the interbed of silt, silty clay and silty sand. More attention should be paid to preparation of model ground, as it is one of the main factors affecting the whole test. Due to randomness of stratum interbed, imitation of one kind of interbed has little significance in experiment. Based on similarity ratio, an equivalent ground as similar as possible with the actual strata was prepared for the model.

The similarity ratios of the model ground parameters are shown in Table 1. To reduce cohesion and modulus of compression, compactness and grain content should be decreased, which will also decrease ground density. In order to satisfy the law of similarity, density consistency should be guaranteed. Therefore, the principle of low elastic modulus and high density of model ground was adopted. The ferroferric oxide powder with properties of non-cohesion and high density was used for preparing the ground to reduce cohesion and compression modulus and increase density. Its effect has been proved in the study of Wang (2012). Besides, the site clay, natural river sands screened by 2 mm sieve and water were also used in preparing the model ground. Based on the similarity ratio, several schemes of material mixture ratio can be obtained, from which the final scheme was determined by numerous preliminary soil tests, as shown in Table 2.

The parameters of natural ground and model ground were obtained by soil strength test. Main parameters of them satisfy the designed similarity ratio overall as shown in Table 1.