Tunnelling and Underground Space Technology 46 (2015) 18–27

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Opening the excavation chamber of the large-diameter size slurry shield: A case study in Nanjing Yangtze River Tunnel in China

Fanlu Min [a], Wei Zhu [b,*], Cheng Lin [c], Xinjun Guo [d]

[a] College of Mechanics and Materials, Hohai University, Nanjing 210098, China
[b] College of Environment, Hohai University, Nanjng 210098, China
[c] Terracon Consultants, Inc., 2201 Rowland Avenue, Savannah, GA 31404, USA
[d] China Railway Fourteenth Group Corporation, Jinan, Shandong 250002, China

ARTICLE INFO

Article history:
Received 4 August 2013
Received in revised form 11 August 2014
Accepted 7 October 2014

Keywords:
Nanjing Yangtze River Tunnel
Slurry shield
Excavation chamber
Filter cake
Compressed air-support

ABSTRACT

Shield tunnel construction in a dense strata often encounters malfunction of shield-tunneling machine or abrasion of cutters. Accessing to an excavation chamber under compressed air is a main method to repair and replace worn cutters. And many safety issues such as stability of the excavation face were involved. However, the face stability due to opening an excavation chamber was not fully studied. To overcome this shortcoming, face support scheme and stability analysis were presented in a case history of opening the pressure chamber for a large-diameter (up to 14.93 m) slurry shield tunnel constructed underneath Nanjing Yangtze River. Since most of the damaged cutters were distributed along the edge of cutting wheel, only top 3 m of tunnel face within the chamber needed to be supported by compressed air, and remaining area would also to be supported by slurry pressure. A series of simple primary laboratory tests were carried out to design an optimum slurries mixing scheme to support the tunnel face as accessing to the pressure chamber in the project. The face stability was analyzed in terms of the pressure equilibrium (i.e., internal and external pressures) as well as three-dimensional numerical analysis by adopting properties of soils and filter cakes from laboratory tests. By injecting lower density slurry into the sand to form a stable infiltration zone, followed by using higher density slurry to create a filter cake at tunnel face, compressed air-support system could ensure face stability during maintenance of cutter wheel. The success of applying the mixed slurry and compressed air-support scheme in this project is valuable to shield tunnel constructions in similar ground conditions.

1. Introduction

With a rapid increase in construction of underground structures in China, shield tunneling has been widely used in the construction activities (Li et al., 2009; Lin et al., 2013; Shang et al., 2004; Wang et al., 2007). Shield tunneling often encounters technical issues such as ground subsidence, lining damage (crack, chipped scale, and leakage) and malfunction of shield machine (Jung et al., 2011; Kavvadas, 2005; Li et al., 2007; Zhang et al., 2011; Tóth et al., 2013). It is not uncommon to open excavation chamber to repair malfunctioned shield tunnel machine, such as cutter abrasion (Hou, 2006; Zhao et al., 2007). However, shield tunnel is often constructed at a great depth below ground surface and/or water level, resulting in large overburden pressures. In many situations, the excavation chamber has to be accessed under compressed air pressure (GEO, 2009), which often involves a great deal of challenge and risk. Thus, stability of tunnel face resulting from opening excavation chambers under high pressures attracted much attention recently.

Opening the excavation chamber is that technicians accessing to the pressure chamber for inspection or repair of the equipment when the dense stratum (e.g. sand, gravel, boulder) is encountered or the tunneling machine has problems (e.g. abrasion of the cutters). If excavation face was initially stable or reinforced, excavation chamber could be open directly without applying support pressures. On the contrary, support pressures were required at tunnel face when it was not stable or could not be reinforced in some situations. In this scenario, compressed air was usually used to support the excavation face. It is always practical and preferred that the excavation chamber is opened without applying supporting pressure (Aydina et al., 2004; Goel et al., 1995). However, it is not always possible to reinforce excavation face in some undesirable

* Corresponding author at: College of Envrionment, Hohai University, 1 Xikang Road, Nanjing 210098, China. Tel.: +86 18652070980; fax: +86 25 83787029.
E-mail address: zhuweiteam.hhu@gmail.com (W. Zhu).

http://dx.doi.org/10.1016/j.tust.2014.10.002
0886-7798/

soil conditions (i.e., highly permeable and coarse-grain soils) under high pore water pressure. Thus, opening the chamber under high pressure is also reported in previous literature (Falk, 1998; Fritz et al., 2002; Heijboer et al., 2004; Jan and Arnold, 2004).

The Nanjing Yangtze River twin tunnels were constructed using two slurry shield Tunnel Boring Machines (TBMs). The tunnels were excavated in fine to coarse sand and located 53.25 m below the water level or 30 m below the existing mudline. Due to the dense sand layers with high Quartz content, cutters on the east TBM were worn severely (Guo et al., 2012; Zhu et al., 2011). Because of large tunnel diameter, high pore water pressure and coarse-grain material encountered in this site, the maintenance of shield machine should be carried out by opening excavation chamber under high pressure. However, the high external soil and water pressure as well as the highly permeable sand caused difficulties in opening the pressure chamber, such as stability of the excavation face, and the safety issue of technicians during the maintenance under high pressure.

So far, limited case studies regarding the opening of excavation chamber were reported in the literature. Falk (1998) conducted a case study to investigate the opening of excavaiton chamber in Elbe Tunnel 4. The slurry shiled tunnel with a diameter of 14.2 m was constructed in Quaternary Glacial Till consisting of sand, marlites, and boulder. It was buried at a depth ranging from 7 to 42 m below the water level. When excavating to the deepest place under the river, the tunnel machine was forced to stop due to the considerable abrasion of the cutters. The technicians had to enter the chamber under pressures of 0.4–0.45 MPa to repair the damaged cutters. Each maintenance lasted for a maximum of 80 min to avoid adverse effects on human being caused by high pressures. It took a total of 2738 h to finish the entire maintenance of the slurry shield machine. The technicians experienced decompression illnesses 21 times after the maintenance in the pressure chamber. In addition, Martin and Bapple (2007) studied the slurry shield used in the construction of one session of the Red Line Subway in St. Petersburg, Russia. The soil encountered was low plastic clay, silty sand, and poorly graded fine sand. The top of the tunnel was approximately 65 m below the ground level, and the water pressure was as high as 0.56 MPa. The cutters were found to significantly wear out to the extent that technicians had to enter the pressure chamber to undertake the maintenance. Every 1.5 h of work inside the chamber required 5 h break outside the chamber for the decompression. In general, the maximum exposure in the pressure chamber was 4.5 h per day.

Several studies (Heijboer et al., 2004; Jan and Arnold, 2004) also explored two slurry shield TBMs used to construct the Westerschelde Tunnel of 11.34 m in diameter and 6600 m in length during the period from 1997 to 2003. The presence of a highly permeable sand stratum located approximately 60 m below water level posed a significant challenge to the progress of the tunneling. Therefore, the chamber was opened at a depth of 45 m below water level in the clay stratum prior to the sand stratum, allowing the technicians to inspect the equipment and replace the abrasive cutters under an air pressure of 0.45 MPa. The decompression time lasted for approximately 2 h. In the meantime, the air pressure inside the excavation chamber was closely monitored to keep a stable excavation surface. The report of abovementioned cases in the literature emphasized the construction process and technicians' health issues. However, limited studies are available on the stability of excavation surface while it also plays key roles in the safety of shield tunneling construction.

In this study, a case history of opening the pressure chamber for a large-diameter (up to 14.93 m) slurry shield tunnel constructed underneath Nanjing Yangtze River was presented. Special attention was paid to the design of an optimum slurry mixed support of tunnel face. Moreover, stability analysis of excavation face was explored by conducting pressure equilibrium (i.e., internal and external pressures) as well as three-dimensional numerical analysis by adopting properties of soils and filter cakes from laboratory tests.

2. Project information of Nanjing Yangtze River Tunnel

2.1. Project site

The city of Nanjing is located in the Yangtze River Delta. By the presence of the Yangtze River, it divides the city into two parts. Fig. 1 shows a schematic of location of Nanjing Yangtze River Tunnel in China. Three bridges have been constructed to connect north-west and south-east areas. With the increasing demand of transportation between two areas, a new line, i.e. the Nanjing Yangtze River Tunnel was constructed. This tunnel represents the first highway tunnel crossing the Yangtze River in Nanjing. The overall length of the tunnel is 5859 m, consisting of a 3020 m slurry shield tunnel from north of the river to Jiangxin Island in the middle of the river, joined by a 2739 m bridge leading to the south main city. The tunnel and the bridge are designed to have bidirectional six lanes. The tunnel with the diameter of 14.93 m is constructed with two slurry shield TBMs made by Herrenknecht of Germany.

2.2. Geology and soil properties

Fig. 2 shows a sectional view of the main geological strata of the Yangtze River. The corresponding soil properties are shown in Table 1. In general, the subsurface soils consisted of clay and silty clay, fine to coarse sand, and mud rock. To determine the friction angle of the clay and silty clay, relatively undisturbed soil samples were taken for conducting consolidated undrained triaxial tests. In total, sixty-two bores were drilled to obtain high-quality soil samples. Before each soil specimen was subjected to shearing, it was consolidated isotropically to the corresponding in-site effective mean normal stress.

At the location of tunnel, the ground consisted of fine sand and coarse sand with high permeability, high quartz content, and low clay content. Large amount of quartz can easily lead to the abrasion of cutters. During the period of the equipment maintenance from August 2008 to December 2008, the average water level was 8.37 m, and the water pressure at the centerline of the TBMs was approximately 0.53 MPa.

2.3. Slurry shield TBM

Fig. 3 shows the cutting wheel and distribution of cutters in slurry shield TBMs used in the project. It was faceplate disc and center supported, with 30% opening ratio and 60–120 cm opening size (Guo et al., 2012). It was consisted of six spokes and equipped with 255 cutters, including 118 immovable scrapers, 16 front scrapers, 12 bucket lips (bolted in every four pieces), six buckets (welded in every piece), 32 rippers, two over cutters (stroke from 0 mm to 40 mm), and 69 exchangeable scrapers. The exchangeable scrapers were distributed alternately all over the cutting wheel. Meanwhile, in these cutters, a total of 10 cutters including eight scrapers and two bucket lips were instrumented with wear detection equipment. The abrasive extent of the cutters was detected by measuring the change of electric current in the electric wire mounted in the cutters. The maximum design torque and thrust force of shield machine were 39,945 kN-m and 199,504 kN respectively, and the rotation rate ranged from 0 to 1.6 rpm.

Fig. 4 shows a schematic of the slurry shield TBM used in the Nanjing Yangtze River Tunnel. The pressure cabin of slurry shield TBM was divided into two chambers by submerged wall, and they