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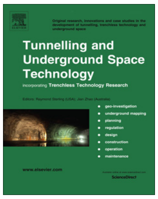

Study on rock mass boreability by TBM penetration test under different in situ stress conditions

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ABSTRACT

Rock mass boreability is a comprehensive parameter reflecting the interaction between rock mass and a tunnel boring machine (TBM). Many factors including rock mass conditions, TBM specifications and operation parameters influence rock mass boreability. In situ stress, as one of the important properties of rock mass conditions, has not been studied specifically for rock mass boreability in TBM tunneling. In this study, three sets of TBM penetration tests are conducted with different in situ stress conditions in three TBM tunnels of the Jinping II Hydropower Station. The correlation between TBM operation parameters collected during the tests and the rock mass boreability index is analyzed to reveal the influence of in situ stress on rock mass boreability and TBM excavation process. The muck produced by each test step is collected and analyzed by the muck sieve test. The results show that in situ stress not only influences the rock mass boreability but also the rock fragmentation process under TBM cutters. If the in situ stress is high enough to cause the stress-induced failure at the tunnel face, it facilitates rock fragmentation by TBM cutters and the corresponding rock boreability index decreases. Otherwise, the in situ stress restrains rock fragmentation by TBM cutters and the rock mass boreablity index increases. Through comparison of the boreability index predicted by the Rock Mass Characteristics (RMC) prediction model with the boreability index calculated from the penetration test results, the influence degree of different in situ stresses for rock mass boreability is obtained.

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1. Introduction

In recent years, TBMs have been a prevailing tunneling method for rock tunnels. As TBM tunneling depends on the interaction between the machine and rock mass, various factors including ground conditions and many environmental constraints, such as fractured rock mass, in situ stress environment and groundwater pressure and ingress and so on, influence the TBM performance. The Commission on Engineering and Technical Systems of USA (1984) defined rock boreability as a value expressing the boring properties of rock in terms of the penetration rate with certain numbers/types of cutters and amount of pressure applied. Rock boreability describes the ease or difficulty with which a rock type can be penetrated by a TBM. Hamilton and Dollinger (1979) used a field penetration index to describe the rock mass boreability, which is defined as the ratio of the applied thrust per cutter to the penetration per revolution. The field penetration index can be calculated from TBM performance. In this paper, the field penetration index is adopted as the rock mass boreability index. Because the boreability index is a function of the thrust, Gong (2005) proposed a Specific Rock Mass Boreability Index (SRMBI) to evaluate the property of the rock mass boreability. The SRMBI is defined as the normal cutter force over the penetration per revolution of 1 mm. It eliminates the influence of the TBM operational parameters on the rock mass boreability (e.g., revolutions per minute, thrust force per cutter). Gong (2005) found that the relationships among the rock mass boreability index, the SRMBI and TBM penetration rate can be estimated as follows:

$$BI = BI_{(1)}P^{-0.75} \tag{1}$$

where BI is the rock mass boreability index; $BI_{(1)}$ is the Specific Rock Mass Boreability Index (SRMBI); P is the penetration rate per revolution.

On the basis of the rock fragmentation mechanism by TBM cutter, Gong and Zhao (2009) explored the influence of the rock mass properties on rock mass boreability and TBM penetration rate. By using the database established from two TBM excavated tunnels

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in Singapore, the SRMBI was obtained based on the rock mass characteristics by using the multiple-variable nonlinear regression analysis (Eq. (2)), and then a Rock Mass Characteristics (RMC) model for TBM penetration rate prediction was proposed by using Eqs. (1) and (2).

$$BI_{(1)} = 37.06 UCS^{0.26} Bi^{-0.10} (0.84 e^{-0.05 J_V} + e^{-0.09 \sin(\alpha+30)}) \quad (2)$$

where UCS is the rock uniaxial compressive strength (MPa); Bi is the rock brittleness index; J_v is the volumetric joint count; α is the angle between the tunnel axis and the joint plane.

The statistical relationship among the rock mass boreability, the specific rock mass boreability and the TBM penetration rate is obtained from the tunnel sites where the in situ stress in the tunnel sites is relatively low compared to the rock strength. Thus, the in situ stress is not considered into the RMC model. The popular existing TBM performance prediction models do not consider the in situ stress parameter due to the lack of the relevant cases. For example, the single factor prediction model that only one of rock material strength parameters (the uniaxial compressive strength, tensile strength, hardness index and so on) was taken into account (Graham, 1976; Farmer and Glossop, 1980; Nelson, 1983) , the Norwegian Institute of Technology (NTH) model (Bruland, 1998) and the Colorado School of Mines (CSM) model (Rostami, 1997; Cheema, 1999). At present, TBMs have been popularly used to construct long tunnels at great depth, such as the Lotschberg Base Tunnel and the Gotthard Base tunnel in Switzerland (Vuilleumier and Aeschbach, 2004; Ehrbar, 2008) and the tunnel group of the Jinping II Hydropower Station in China (Gong et al., 2012). Due to the great overburden and structural stresses, the complex in situ stress condition becomes a key parameter influencing rock mass boreability and TBM performance. For example, Bordet and Comes (1975) confirmed that rock boreability decreased by almost 30% under high stressed confinement (at the stress level of about 30–50 MPa) through laboratory tests. Gehring (1995) found that the disc cutter consumption for TBM tunneling under high overburden (800 m) was greater than that under lower overburden even in similar rock conditions. The phenomenon was thought mainly due to the higher thrust requirement for the TBM advance under higher stressed confinement. However, some opposite experiences were reported for some sites where the favorable effect of in situ stress on the TBM advance was observed (Tarkoy and Marconi, 1991; Klein et al., 1995). Thus, it is necessary to thoroughly investigate the influence of in situ stress on rock mass boreability for TBM tunneling in order to evaluate TBM applicability and improve excavation efficiency.

As one of the most vigorous methods to explore the rock mass boreability with a certain rock mass condition, the TBM penetration test can consider the influencing factors from three aspects: (1) machine specifications including cutterhead diameter, disc cutter diameter, cutter spacing and cutter wear; (2) rock mass properties and conditions: rock strength, brittleness, joint space and direction and excavation environment including in situ stress and groundwater and so on; (3) TBM operation parameters including TBM rotation rate, thrust force and torque. In this study, three sets of penetration tests are carried out in three tunnels with different in situ stress conditions at the Jinping II Hydropower Station for exploring the influence of in situ stress on rock mass boreability and TBM performance.

2. Brief description of the sites

The Jinping II Hydropower Station is located in Sichuan Province, southwest China. It is mainly composed of an intake structure, powerhouses and four long headrace tunnels i.e. HT01, 02, 03 and 04 (Fig. 1). Before excavating the four headrace tunnels, two auxiliary tunnels parallel to the four headrace tunnels in the southern side have been constructed using the drill-and-blast method for transportation from the Jinping II Hydropower Station to the Jinping I Hydropower Station. During excavation of the auxiliary tunnels, the problems induced by high in situ stress and large groundwater inflow were encountered. A drainage tunnel was then excavated to divert the inflow water before the headrace tunnels excavating. Among these tunnels, the HT01 and HT03 were constructed by two hard rock TBMs with the diameter of 12.4 m and the drainage tunnel was excavated by a TBM with the diameter of 7.2 m.

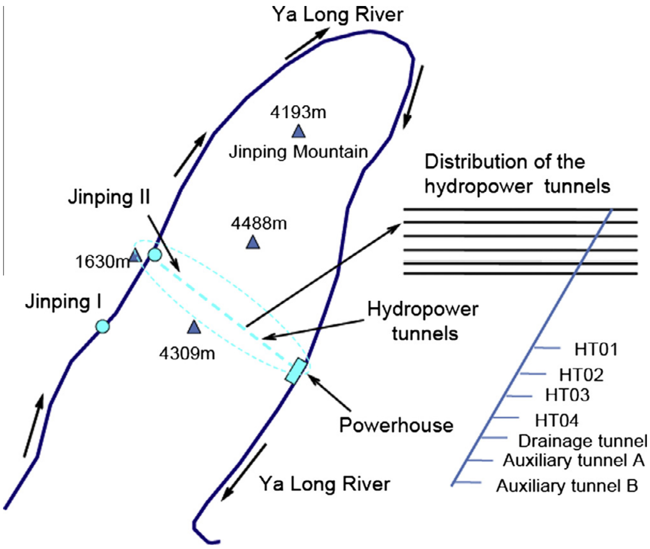

Fig. 1. Layout of the Jinping II Hydropower Station.

The geological structure in this region, controlled by the NWW∼SEE stress field, is composed of a series of close complex folds from south to north and high inclined angle piezotropy rupture accompanied extension fault in the NWW direction. The strike of the steep bed is parallel to the direction of principal tectonic line, as shown in the geological cross section profile (Fig. 2). The overburden along these tunnels is generally great. More than 70% of overburden along these tunnels is greater than 1500 m and the maximum overburden is up to 2525 m.

In order to investigate the in situ stress of Jingping project, the hydro-fracturing tests in boreholes and relief tests were conducted in two auxiliary tunnels by East China Investigation and Design Institute (ECIDI, 2009). The result of in situ stress measurement in the tunnel region shows that in situ stress increases with increasing cover depth and in situ stress changes from predominantly the horizontal stress state to the vertical stress state with the cover depth varying from 600 to 2500 m. The maximum in situ stress obtained from the survey reaches to 42.11 MPa. According to the in situ stress survey, the back-analysis and regression analysis were conducted. The regression curve of in situ stress along the depth of auxiliary tunnel was obtained and shown in Fig. 3.

3. Penetration tests and rock mass boreability analysis

3.1. Penetration tests

For the Jinping II Hydropower Station, the HT01, HT03 and the drainage tunnel were excavated by TBMs. The TBM penetration tests were carried out in the three tunnels under different overburden depths, namely different in situ stress conditions. The design

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