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A case study of TBM performance prediction using a Chinese rock mass classification system – Hydropower Classification (HC) method

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ABSTRACT

Basic Quality (BQ) method is a basic national standard of rock mass classification suitable for different industries in geomechanics and geotechnical engineering in China. Referring to the relevant provisions of BQ method, Hydropower Classification (HC) method, a specialized engineering geological classification system widely used in China, was compiled for evaluation on overall stability of surrounding rock and guide of excavation and support design of underground engineering in water conservancy and hydropower industry. As the input parameters of BQ or HC method are quite different with those used in RMR or Q system, which indirectly limits the applicability of the foreign developed TBM performance prediction models for the China's TBM tunnelling projects. In order to develop an empirical model for hard rock TBM performance prediction with more suitable applicability in China, 49 valid datasets were collected from a water conveyance tunnel mostly excavated in medium to hard igneous rocks, and the empirical relationships between TBM performance and each parameter in the database were studied. The results showed that the prediction accuracies of TBM performance based on *HC* or *BQ* are very limited as the effects of the input parameters of HC method on field penetration index (*FPI*) are different and their weights assigned are improper. TBM penetration rate (*PR*) reaches its maximum value in the *HC* range 40–60 and *BQ* range 350–450, respectively. Boreability of the rock mass in class III is higher than that in class II. Ridge regression, principal component regression and partial least-squares regression methods were employed to solve the multicollinearity between uniaxial compressive strength of intact saturated rock, intactness index of rock mass, angle between discontinuity plane and tunnel axis, and average overburden of tunnel section in the database. Comparisons between the measured *FPI* and predicted *FPI* showed good agreement. This highlights the powerful potential of multiple regression analysis model based on HC method in TBM performance prediction. However, it deserves to emphasize that the developed empirical relationships should be considered valid only for new projects with geological conditions similar to the studied tunnel in this study, and more field data from different projects need to be collected to develop a universal model in the future.

1. Introduction

With the rapid development of modernization in China, hard rock tunnel projects of various diameters, lengths and overburdens are being widely constructed in water conservancy and hydropower, transportation, mining and other industries. China has already been the country with the fastest development speed, largest construction scale and highest construction difficulty of tunnel excavation in the world currently. As stated by Reilly et al. (2002): "mechanized tunnel excavation and advanced underground construction technologies are regarded as one new field of the 21st century by the western countries, so it can generally be named the century of tunnel engineering". Tunnel boring machine (TBM) has been widely used in hard rock tunnelling for its fast advance rate, high excavation quality, favorable environmental protection, low labor intensity (Qian and Li, 2002). By incorporating the latest technological achievements in mechanical, hydraulic, optical and electrical engineering, TBM has been updated to a large scale and high technical tunnel construction equipment that can

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conduct tunnelling, mucking, guiding and supporting simultaneously. Since its first successful employment in 1990s, more than 50 tunnels have been completed in China so far through absorbing the accumulated experience of TBM tunnelling projects in the past 50 years in western countries. According to the related statistics, tunnels with total length more than 4000 km will be constructed by about 130 TBMs in the next 10 years in China (Liu et al., 2016a). Pelizza et al. (2002) indicated that, with the largest construction scale never encountered by western countries, the Western China Development will provide a unique opportunity for the implementation of TBM tunnelling method.

With high sensitivity to varying geological conditions and enormous financial investment in initial project phase, accurate prediction of TBM performance with respect to special ground conditions has a crucial importance for arranging construction schedule and assessing excavation cost. However, it is always quite difficult to reveal the genuine correlation between TBM performance and rock mass properties deeply due to the extremely complex interaction mechanism of rock-machine. In the past three decades, a large number of TBM performance prediction models have been developed and these models can be generally divided into two main categories, i.e. theoretical and empirical ones (Rostami et al., 1996). Based on rock fragmentation mechanism, theoretical models, e.g. CSM model (Rostami, 1997), analyze the cutting forces acting on individual disc cutter to obtain the force equilibrium equations through indentation tests or full-scale linear cutting tests (Roxborough and Phillips, 1975; Snowdon et al., 1982; Sanio, 1985; Rostami and Ozdemir, 1993; Rostami, 1997). As the theoretical models are limited by the available test facilities and the effects of joint conditions on the cutting process are not considered, empirical formulas based on field data are more convenient to master by constructors, and thus widely developed and preferred in TBM performance prediction (Tarkoy, 1973; Graham, 1976; Blindheim, 1979; Farmer and Glossop, 1980; Nelson et al., 1983, 1985; Bamford, 1984; Hughes, 1986; Wijk, 1992; Sundin and Wänstedt, 1994; Laughton, 1998; Bruland, 1998; Alvarez Grima et al., 2000; Ribacchi and Lembo-Fazio, 2005; Yagiz, 2008; Gong and Zhao, 2009; Hassanpour et al., 2009, 2010, 2011). Empirical models have been improved from simple ones to complex ones. The early simple empirical models which are no longer used for their low prediction accuracy only considered a few intact rock mechanical properties, e.g. compressive strength, tensile strength and hardness. With accessibility to more TBM construction data, several complex empirical models have been established by researches using multiple regression analysis, fuzzy mathematics, neural network and so on, and NTNU model (Bruland, 1998) is the best known one. Prediction accuracy of the complex empirical models depends largely on the similarity degree of the ground conditions, machine specifications and operation parameters between the target tunnel and the original database, and higher similarity degree generally leads to more accurate prediction results. At present, TBM performance prediction models for specific geological conditions are still rarely developed, e.g. mixed grounds (Steingrimsson et al., 2002; Zhao et al., 2007; Tóth et al., 2013), grounds with toxic gases (Shahriar et al., 2009), blocky rock conditions (Delisio et al., 2013, Delisio and Zhao, 2014), highly fractured and faulted rock conditions (Paltrinieri et al., 2016), thus deeper investigation and research about these specific ground conditions need to be conducted in the future.

Comparing with more than 30 TBM performance prediction models available in foreign published literatures, only two simple empirical models are reported by Chinese researchers (Song et al., 2008; Du et al., 2015). TBM performance is the comprehensive interaction result between the machine and excavated rock mass. Liu et al. (2016b) counted the using frequency of rock mass properties and machine parameters in total 17 models, including theoretical models and complex empirical models, and found that the using frequency of rock mass properties decreased in the order of discontinuity spacing (15 times, including *RQD*, J_v, J_s and *CFF*), intact rock uniaxial compressive strength (12 times), angle between the discontinuity and the tunnel axial (6 times), tunnel diameter (5 times), rock brittleness (4 times, including *PSI* and S_{20}) and so on, and the using frequency of machine parameters decreased in the order of equivalent thrust per cutter (8 times), revolutions per minute (4 times), cutter diameter (3 times), cutter spacing (2 times), cutter tip width (1 time) and angle of the contact area between rock and disc cutter (1 time).

As most of the rock mass properties used for TBM performance prediction are related to the input parameters of rock mass classification systems, some researchers attempt to link TBM performance with these systems (Cassinelli et al., 1982; Innaurato et al., 1991; Mcfeat-Smith and Askilsrud, 1993; Grandori et al., 1995; Palmström, 1995; Sundaram and Rafek, 1998; Barton, 1999; Alber, 2000; Sapigni et al., 2002; Ribacchi and Lembo-Fazio, 2005; Bieniawski et al., 2006, 2007a, 2007b, 2008; Bieniawski and Grandori, 2007; Hassanpour et al., 2009, 2010, 2011; Hamidi et al., 2010). However, the input parameters of RMR (Bieniawski, 1989) or Q system (Barton et al., 1974) are quite different with those used in BQ (The National Standards Compilation Group of People's Republic of China, 2014) or HC method (The National Standards Compilation Group of People's Republic of China, 2009), the two commonly used rock mass classification systems in China, which indirectly limits the applicability of the foreign developed TBM performance prediction models for the China's TBM tunnelling projects. Therefore, this study attempts to develop an empirical model for hard rock TBM performance prediction based on multiple regression analysis of HC method.

2. Basic Quality (BQ) method and Hydropower Classification (HC) method

Standard for engineering classification of rock masses (GB/T50218-2014), BQ method for short, provides one necessary and fundamental basis for the exploration, design, and quota compilation of rock engineering construction. It combines both the qualitative and quantitative methods to determine the basic quality of rock mass, and then takes the characteristics of the specific engineering into account to obtain the rock mass classification (The National Standards Compilation Group of People's Republic of China, 2014). Considering the extremely complex nature of rock mass, compilation of such a basic national standard is the first attempt for different industries in geomechanics and geotechnical engineering in the world. The reliability of BQ method has been verified in water conservancy and hydropower, transportation, railway, and mining projects since it was implemented in China (Wu and Liu, 2012). *BQ* is determined in accordance with two basic factors, namely intact rock strength and rock mass intactness degree, and can be calculated using Eq. (1) (The National Standards Compilation Group of People's Republic of China, 2014):

$$BQ = 90 + 3 * R_c + 250 * K_v \quad (1)$$

where *BQ* is the rock mass rating of BQ method, R_c is the uniaxial compressive strength of intact saturated rock (MPa), K_v is the intactness index of rock mass.

It deserves to emphasize that two restricted conditions should be obeyed when using Eq. (1), i.e. 1. Substituting $R_c = 90 * K_v + 30$ and K_v into Eq. (1) to obtain *BQ* when $R_c > 90 * K_v + 30$; 2. Substituting $K_v = 0.04 * R_c + 0.4$ and R_c into Eq. (1) to obtain *BQ* when $K_v > 0.04 * R_c + 0.4$. The corresponding rock mass classification of BQ method is shown in Table 1.