Tunnelling and Underground Space Technology 69 (2017) 116–124

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Prediction of TBM performance in mixed-face ground conditions

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ARTICLE INFO

Keywords:
Tunnel boring machine
TBM
Mixed-face
Granite
Ground model
RMR

ABSTRACT

A significant number of TBM performance prediction models in full-face soil or rock conditions are available in literature. However, very few prediction models exist for tunnels excavated in mixed-face ground conditions, mainly due to the complexity of the ground.

Tunnelling in areas where two or more materials with significantly different geotechnical properties are simultaneously encountered on the tunnel face has often been described as one of the most challenging tunnelling scenarios. In such cases tunnel face instabilities are common and a thorough geotechnical assessment is necessary in order to select the most appropriate tunnelling technique.

TBM performance for tunnels in mixed-face conditions was studied, based on the analysis of data from a tunnel project in Singapore excavated into Bukit Timah Granite. The areas considered are located within granite characterised by different weathering grades, which frequently results in mixed-face ground conditions represented by varying percentages of rock and soil simultaneously present at the tunnel face.

A new TBM performance prediction index was proposed for mixed-face ground conditions, named as Mixed-face Penetration Index (MFPI). MFPI accounts for the total thrust force exerted by the TBM on the tunnel face (MN) and for the penetration rate (mm/rev). The index was correlated with: (a) the percentage of rock on the tunnel face, (b) the uniaxial compressive strength (UCS) of intact rock and (c) the rock quality designation (RQD) of rock mass, by using a weighted rock mass rating of the tunnel face (RMR_m). Although no correlation was determined between MFPI and the geotechnical properties of the soil, its presence was considered in the TBM performance prediction model by assigning an RMR value to the soil portion equal to zero.

MFPI and RMR_m were correlated using regression analysis tools. The proposed relationship between these two indexes has been validated based on the recorded data of TBM performance in mixed-face ground along the excavated tunnel in Bukit Timah granite.

1. Introduction

Projects where TBM's are selected as the excavation method are usually colossal, involving many different parties, stages and huge investments. In order to synchronize the different contractual parties and project stages meeting schedules is a must. Failing to meet project schedules might threaten the profitability of the whole project. The latter justifies the many attempts carried out in the last 30 years in order to predict TBM's performance.

A broad range of models to forecast TBM's performance either in rock (e.g. Norwegian University of Science and Technology, NTNU; Colorado School of Mines, CSM; Q_{TBM} models) or soil (e.g. Benardos and Kaliampakos, 2004) have been developed, each one of them considering different geotechnical and TBM parameters. However, only two models have been developed for tunnels in mixed-face ground conditions, namely by Steingrimsson et al. (2002) and Tóth et al. (2013), which both don't consider the geotechnical properties of the ground.

In the present paper, a new model is proposed to predict TBM performance in tunnels excavated in mixed-face ground conditions, based on the analysis of data from tunnel projects in Singapore. The model considers selected geotechnical properties of the materials present on the tunnel face.

2. Literature review

2.1. TBM performance in hard rocks and faulted rock mass

The key parameters on the estimation of tunnel-boring machine (TBM) performance in hard rocks are rock strength, toughness,

Abbreviations: FPI, field penetration index; MFPI, mixed-face penetration index; RMR_m, weighted rock mass rating of materials present on the tunnel face

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http://dx.doi.org/10.1016/j.tust.2017.06.015
Received 19 December 2016; Received in revised form 17 May 2017; Accepted 9 June 2017
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discontinuity characteristics, type and specifications of TBM. Originally, the most recognized TBM performance prediction models in hard rock are the Norwegian University of Science and Technology (NTNU) model proposed by Blindheim (1979) and the Colorado School of Mines (CSM) proposed by Rostami and Ozdemir (1993). The latter was modified by Yagiz (2002) by incorporating the brittleness index (BI) and the rock fracture index (RFI) in the regression model.

Barton (1999, 2000) proposed a new model to estimate TBM penetration and advance rate based on Q rock mass classification system, Q_{TBM}, which uses many input parameters (such as RQD, joint condition, stress condition, intact rock strength, quartz content and TBM thrust). Sapigni et al. (2002) used rock mass classification to estimate TBM performance. Yagiz (2008) proposed an empirical equation for estimation of TBM penetration rate based on uniaxial compressive strength, toughness, orientation of discontinuities and TBM drive direction and discontinuity distance. Hassanpour et al. (2011) linked geological parameters (UCS, joint spacing and RQD) and TBM performance (Field Penetration Index, FPI) and proposed a new hard rock TBM performance prediction model. Gong and Zhao (2009) proposed a statistical prediction model of TBM penetration rate and showed that the rock uniaxial compressive strength and the volumetric joint count have predominant effects on the penetration rate.

Cho et al. (2013) studied the cutting performance of TBM disc cutters by a Linear Cutting Machine test for a granitic rock in Korea and demonstrated the applicability of numerical analysis as an alternative for the prediction of the cutting performance. Gong et al. (2007) conducted a series of TBM shield friction tests in order to compare rock mass boreability in different rock mass conditions. They concluded that penetration per revolution increases rapidly with increasing thrust per cutter when it is higher than a critical value.

Some researchers developed fuzzy logic models to predict the penetration rate based on data from hard rock TBM tunnels (Alvarez Grima et al., 2000; Ghasemi et al., 2014).

Barla and Pelizza (2000) presented different case studies of TBM tunnelling in difficult ground conditions. Shahriar et al. (2008) proposed a new approach for TBM selection in difficult ground conditions based on decision analysis using decision tree and on geotechnical risk minimization.

Delisio et al. (2013) focused on TBM performance in blocky rock conditions in the Lotschberg base tunnel. They proposed a relationship between Field Penetration Index (FPI) and rock mass conditions (volumetric joint count, J_v, and the intact rock uniaxial compressive strength, UCS).

Macias et al. (2014) studied the influence of rock mass fracturing on the net penetration rates of hard rock TBMs and correlated net penetration rate with the fracturing factor (k_s), which was used to include the influence of rock mass fractures. Paltrinieri et al. (2016) analyzed gripper TBM performances in highly fractured and faulted rocks and concluded that scattered results between penetration rate and rock mass parameters, confirm the difficulties in predicting the machine performance in complex geological environments.

Hassanpour et al. (2011) and Delisio et al. (2013) present a complete list of existing prediction models for hard rocks and fractured rock masses.

Yagiz (2017) studied the TBM performance in fractured rock masses and presented a series of equations for predicting the field penetration index (FPI) utilizing intact and rock mass properties.

2.2. TBM performance in mixed-face conditions

According to Tóth et al. (2013), mixed-face ground is the ground where there are two or more geological materials simultaneously present on the tunnel face with significant differences in material properties that influence the TBM penetration rate or operational parameters of TBM or support system installed behind the TBM.

Industry has accepted a definition of mixed-face condition, where the uniaxial compressive strength (UCS) ratio is at or lower than 1/10 between that of the weakest and strongest material (Tóth et al., 2013).

In mixed-face conditions, the cutters working on the stronger part of the face are taking up more thrust than the cutters on the weaker part (Steingrimsson et al., 2002). As the cutters move over the face they are taking up highly variable loads and the result of such loading is cutter wear and failure.

A discussion on the theory of cutting in mixed face conditions is given by Zhao et al. (2007). According to them, when soil dominates at the tunnel face, the soft material is not capable of generating enough rolling force for cutters to overcome the pretorque of the cutter bearings, resulting in frequent stoppages of cutter rotation. A short stoppage of cutter rotation can lead to a small flat wear of the cutter, and then the cutting force and torque developed at that cutter may reduce. This occurs until the cutter cannot rotate at all thus more loads are exerted on adjacent cutters.

As stated earlier, only two models have been proposed to predict TBM performance for tunnels in mixed-face ground conditions. Existing models for such conditions utilize either the penetration rate (mm/rev) or the net advance rate (m/day or rings/day), as representative indexes of the TBM data set.

Steingrimsson et al. (2002) proposed a correction factor to adjust the performance prediction by taking into account the effects of the mixed-face. In this approach, the measured or calculated penetration rates from the homogenous faces are used as a proportional strength indicator for the mixed-face components. The penetration rate is reduced according to the inverse proportion of the penetration rate in the stronger layer (I_A) and the average penetration rate (I_{AB}) of the two layers on the face.

Tóth et al. (2013) compared the measured penetration rates with those calculated by Steingrimsson et al. (2002) model and concluded that penetration rate (mm/rpm) decreases with increasing percentage of the hard portion on the face. Hongsu et al. (2015) presented a review of problems and solutions of TBM tunnelling in mixed-face ground. Shirlaw (2016) provided a review of problems encountered during pressurised TBM tunnelling in mixed-face conditions resulting from tropical weathering of igneous rock in Singapore.

3. Geotechnical input

3.1. Ground model

Singapore has a tropical climate, which is characterised by high annual rainfall (average of 2200 mm per annum) and constant and high temperatures all year-round (maximums of 30–32 °C). As a result, the geology of the island is highly affected by chemical decomposition (Zhao et al., 1994), which gives place to weathering profiles characterised by abrupt changes between different weathering grades.

This study is focused in metro projects located in the centre of Singapore where Bukit Timah granite is found forming a batholith, extending around 8.5 km from north to south and 7 km from east to west. Despite being described as granite, it actually refers to a range of acidic igneous rocks, which include granodiorite and adamellite to true granite (Sharma et al., 1999). Small dikes of both doleritic and aplitic composition intrude this formation. Bukit Timah granite is overlaid in this area by more recent alluvial deposits and made ground.

The geological cross section of the studied section is presented in Fig. 1 and was based on borehole logs and observations from weekly tunnel progress reports. Despite the fact that the spacing between boreholes was relatively small (average spacing of 52 m), it proved difficult to distinguish zones with similar lithology between adjacent boreholes due to the high vertical and horizontal variability of the geological structure. Similar ground conditions in weathered granites resulting in heterogeneous rock masses have been encountered in the case of “Metro do Porto” (Babendererde et al., 2004).

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