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A new method for selecting hard rock TBM tunnelling parameters using optimum energy: A case study

Ya-dong Xue[a,*], Feng Zhao[a], Han-xiang Zhao[a], Xing Li[a], Zhen-xing Diao[b]

[a] Department of Geotechnical Engineering, Tongji University, Shanghai, China
[b] Shanghai Nuclear Engineering Research & Design Institute Co., Ltd., Shanghai, China

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ABSTRACT

In this study, a new method for selecting hard rock TBM tunnelling parameters is established using optimum energy. Several concepts on energy, such as specific energies in tunnelling, E_s^t, rock crushing, E_s^r, and friction, E_s^f, are proposed and their relationships in the TBM tunnelling process are analyzed. Moreover, a new formula for calculating the tunnelling specific energy, E_s^t, considering three factors—geological parameters, TBM technical specifications, and rock-machine interaction relationship—is presented. In order to study the optimum tunnelling parameters, a series of preliminary full-scale disc cutting tests are conducted using the TJ-TS500 linear cutting machine (LCM). The LCM tests show that for a specific type of rock, there is an optimum spacing to penetration ratio (s/p) based on the optimum rock crushing specific energy, E_s^r. To obtain the optimum value of s/p for different rocks, the laws of the optimum s/p and rock uniaxial compressive strength are obtained by data regression. Based on these rules, TBM tunnelling under specific geological conditions, not only can the optimum penetration be obtained, but also the optimum E_s^t and the optimum tunnelling parameters can be calculated. This method provides an evaluation standard for selecting TBM tunnelling parameters, and links the LCM test with the actual TBM tunnelling process using the energy method. Furthermore, to illustrate the applicability of this method, a case study of the Yinhanjiwei headrace project is introduced and analyzed in detail. By comparing the actual with optimum tunnelling parameters, the study proves that this new method is rational and that it can be used to select the optimum tunnelling parameters in hard rock TBMs.

1. Introduction

In recent years, with the acceleration of infrastructure construction and urbanization, tunnel boring machines (TBMs) are widely used in hard rock tunnel excavations for its fast advance rate, high excavation quality, favorable environmental protection, low labor intensity (Qian and Li, 2002). According to the infrastructure construction plan, more than 130 TBMs will be used to excavate a total length of more than 4000 km of tunnels in China (Wang, 2014). Currently, China already has the world's fastest development speed, largest construction scale, highest degree of construction difficulty in tunnel excavation (Liu et al., 2017). Considering the safety, duration, cost of tunnel construction, and realization of the overall optimization, two aspects need to be considered: the selection of equipment before construction and the control of operation in construction.

In terms of equipment selection before construction, in order to reasonably predict the duration and cost of the project, many scholars have developed a large number of TBM performance prediction models based on geological conditions and engineering characteristics of different projects. Among them, the most widely used and recognized are the model created by the Colorado School of Mines or CSM model (Rostami, 1997; Rostami and Ozdemir, 1993; Rostami et al., 1996) and that of the Norwegian University of Science and Technology or NTNU model (Bruland, 1998). Based on the rock fragmentation mechanism, the CSM model analyzes the cutting forces acting on individual disc cutters to obtain the force equilibrium equations through indention tests or full-scale linear cutting tests (Roxborough and Philips, 1975; Sanio, 1985). Because the theoretical models are limited by the test facilities and the effects of joint conditions are not considered, many researchers have worked to develop new empirical prediction models or common adjustment factors for existing models (Yagiz, 2002, 2008; Ramezanzadeh, 2005; Gong and Zhao, 2009; Hassanpour et al., 2009, 2010; Dudt and Delisio, 2015). Moreover, other prediction models have also been developed in recent years from the perspective of rock classification. Barton (2000) reviewed a wide range of TBM tunnels to establish a database for proposing a new model named Q_{TBM} based on the Q rock classification. Sapigni et al. (2002) studied the empirical relationship between rock mass rating (RMR) and penetration rate.

* Corresponding author.
E-mail address: yadongxue@126.com (Y.-d. Xue).

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Nomenclature

E	specific energy, kWh/m^3
$E_s{}^t$	tunnelling specific energy, kWh/m^3
$E_s{}^r$	rock crushing specific energy, kWh/m^3
$E_s{}^w$	wear specific energy of disc cutter wear and cutterhead, kWh/m^3
$E_s{}^f$	friction specific energy, kWh/m^3
$E_s{}^m$	muck discharging specific energy, kWh/m^3
$E_s{}^{t\prime}$	theoretical tunnelling specific energy, kWh/m^3
Th	total thrust of cutterhead, kN
Tor	total torque of cutterhead, kN
R_t	radius of excavated tunnel, m
D	diameter of the excavated tunnel, m
R	disc cutter radius, mm
p	penetration per revolution, mm/rev
φ	angle corresponding to whole contact arc length of interaction, rad
μ	friction coefficient *
M	quality of the cutterhead and a part of the TBM, excluding the back-up system, t
F'	normalized resultant force, kN
F_n	normal force acting on disc cutter, kN
F_r	rolling force acting on disc cutter, kN
F_s	side force acting on disc cutter, kN
CC	cutting coefficient *
N	number of disc cutters *
r_i	installation radius of the ith cutter in the cutterhead, m
S_i	spacing between the ith cutter and $(i-1)$th cutter in the cutterhead, m
α	reduction coefficient *
FPI	field penetration index, kN/m/mm/rev
UCS	uniaxial compressive strength, MPa
K_v	intactness index of rock mass *
g	gravity acceleration, m/s^2
ρ	density of the excavated rock, kg/m^3
h	height between the bottom of the tunnel and machine belt, m
*	dimensionless

Delisio and Zhao (2014) developed a model for TBM performance estimation in blocky and jointed rocks based on a modified version of the field penetration index (FPI). It can be seen that current performance prediction models are based on laboratory tests and on-site statistics. The laboratory tests focused on mechanism analysis, mainly used in the disc cutter design and selection, whereas on-site data are mainly used to predict and evaluate the adaptability of the equipment. In practical applications, the mechanism of rock breaking by disc cutters and the adaptability of the equipment should be more systematically considered and analyzed.

In the actual TBM tunnelling process, one of the biggest problems is to select the tunnelling parameters of TBMs to reach an efficient tunnelling state. Furthermore, under different geological conditions, how to more reasonably determine the TBM tunnelling parameters has become the primary problem of constructors and TBM main drivers. Currently, because there is no quantitative standard for selection of TBM tunnelling parameters, it is often based on engineering experience. The main driver of the TBM usually sets the rotational speed of the cutterhead and the advance rate of the TBM by monitoring the electric current of the equipment, which is also often based on engineering experience (Zhou et al., 2009; Lu et al., 2016). Evidently, research on selecting the optimum TBM tunnelling parameters has been limited.

The energy method, as a commonly used analytical method, has been extensively used in seismic, blasting, and other engineering fields. In the field of TBM, several research have also studied the problems in the process of TBM tunnelling from the perspective of energy, such as the prediction of the disc cutter wear (Wang et al., 2012, 2015; Yang et al., 2015) and the evaluation of the rock breaking efficiency (Gong et al., 2016, 2017), all of which provide some reference basis for our investigation. In this study, a new method for selecting hard rock TBM tunnelling parameters using optimum energy is established. Based on the energy analysis of the TBM system, the energy relationship between geological conditions and the TBM construction performance is established by combining the results from the linear cutting machine (LCM) tests and on-site data. The energy conversion in the TBM tunnelling process is analyzed and each part of the energies are briefly calculated. Through the LCM tests, the relationship between the ratio of cutter spacing (***S***) to the penetration(***p***), ***S/p***, and the specific energy of different rocks is obtained. Based on the optimum energy, the optimum tunnelling parameters of TBM, such as thrust and torque, are obtained by optimizing the penetration. The quantitative evaluation standard of the TBM operation control performance based on energy is achieved. Finally, a case study of the Yinhanjiwei headrace project is introduced and analyzed in detail to prove the rationality of this new method.

2. Energy analysis in hard rock TBM tunnelling

During the hard rock TBM tunnelling process, the total input energy is achieved through the TBM thrust and torque. The output energy includes rock mass breakage, cutter wear, and muck discharging. However, in the LCM tests, almost all of the input energy is used to break the rock, which is also one of the differences between the LCM tests and TBM tunnelling process. As an aid in selecting TBM tunnelling parameters, the energy conversion during TBM tunnelling is analyzed. Several concepts of the specific energy are first proposed, and thereafter, their calculation methods, including specific energies in tunnelling, $E_s{}^t$, rock crushing, $E_s{}^r$, wear of disc cutters and cutterhead, $E_s{}^w$, friction, $E_s{}^f$, and muck discharging, $E_s{}^m$, are analyzed.

2.1. Definition and calculation of specific energy

(1) Tunnelling specific energy, $E_s{}^t$

The $E_s{}^t$, which is defined as the total energy input from the thrust and torque to excavate a unit volume of rock during the TBM tunnelling process, is one of the primary parameters used to determine the TBM performance. Actually, the $E_s{}^t$ is a comprehensive parameter reflecting the result of the interaction between the rock masses and TBM (Wang et al., 2012). Liu (2002) proposed the calculation formula for it, as follows:

$$E_s^t = \frac{Th\cdot p + 2\pi Tor}{\pi R_t^2 p}. \tag{1}$$

In Eq. (1), $E_s{}^t$ is the tunnelling specific energy; Th and Tor are the TBM thrust and torque force, respectively; p represents penetration per revolution; R_t is the radius of the excavated tunnel.

(2) Rock crushing specific energy, $E_s{}^r$

The rock crushing specific energy, $E_s{}^r$, which is the energy required to break the unit volume of rock, is part of the $E_s{}^t$. It should be noted that $E_s{}^r$ is the same as the specific energy, ***SE***, measured by the LCM test and can be calculated it. However, because the LCM test is usually expensive and time-consuming, it is reasonable to perform a three-dimensional numerical analysis to simulate the rock cutting behavior to obtain the value of $E_s{}^r$ (Cho et al., 2013). Several research have also found that the ***SE*** in the LCM test is related to the ratio of the cutter spacing to penetration, as well as rock properties (Rostami and