INFLUENCE ANALYSIS OF ROCK MECHANICAL PARAMETERS ON THE TBM PENETRATING RATE

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ABSTRACT

To study the influences of rock mechanical parameters on the penetrating rate of a tunnel boring machine (TBM), a 3D discrete element model, namely, 3D distinct element code (3DEC), was used to build simulated models on rock fragments using a TBM cutter based on the geological conditions of the west route of the South-to-North Water Transfer Project. The change rule of the TBM penetrating rate caused by different rock mechanical parameters was analyzed. The line graph of the relationship between the TBM penetrating rate and rock mechanical parameters was fitted using the least squares method. Results show that the TBM penetrating rate will decrease with an increase in uniaxial compressive strength and elastic modulus. By contrast, it will increase with an increase in rock Poisson's ratio. This finding is in accordance with the result of the finished project. A numerical foundation was provided for the TBM tunneling of diversion tunnels in the west route of the South-to-North Water Transfer Project.

KEYWORDS

TBM; Penetrating rate; Rock mechanical parameters; Discrete element model; Least squares method

INTRODUCTION

The tunnel boring machine (TBM) has been widely used in domestic and overseas deep tunnels (hereafter referred to as the TBM construction method) because of its high construction efficiency, good forming construction, and impact on the safety and small operation of the surrounding environment [1–3]. Many geological factors affect the TBM tunneling rate due to the geological conditions in front of the construction area that result in poor TBM adaptability. These factors can be mainly divided into three categories: lithology, rock hardness difference, and geological disasters [4–5]. Rock mechanical parameters are important factors that affect the TBM tunneling rate. In recent years, numerous local and overseas scholars have analyzed factors that influence the TBM tunneling rate via geological field surveys, laboratory rock mechanical tests, and numerical simulations. Li discussed the relationship of rock uniaxial compressive strength (UCS) and hardness to the TBM penetration rate [6]. Wang described the relationship between the tunneling rate and geological factors of tunnel excavation [7]. Luo utilized the function fitting model to investigate the UCS and abrasion value of rocks and their correlation [8]. Vicente et al. used the Monte Carlo–backpropagation neural network method to predict the TBM tunneling rate [9]. Qin studied the characteristics of rock excavation using TBM when the decision problem of [10]. He discussed the classification method for the TBM construction of tunnel surrounding rock under the condition of [11]. However, the aforementioned studies on TBM have not conducted a systematic numerical analysis of the relationship between the TBM tunneling rate and rock mechanical parameters. In the current study, a 3D discrete element program, namely, 3D distinct element code (3DEC), is used to simulate the rock-breaking process of a TBM hob. The influences of rock mechanical parameters on the TBM tunneling rate are also analyzed.

ROCK MECHANICAL PARAMETERS THAT AFFECT THE TBM TUNNELING RATE

Rock mechanical parameters related to the TBM tunneling rate can be expressed using indexes of rock UCS, elastic modulus, and Poisson's ratio. The tool penetration depth factor is the most important mechanical behavior of rocks under uniaxial compression conditions. A rotary tool must exert a force that is greater than the strength of rock stress to effectively cut into the rock; hence, the TBM tunneling rate and rock UCS are closely related. Existing engineering experience indicates that rock UCS is low within a certain range, and the TBM driving rate is high. When rock UCS increases, the TBM driving rate is decreased. However, when rock UCS is too low, the self-stability of the surrounding rock decreases, collapse can easily occur, and the TBM penetration rate is reduced. When TBM is driven into hard-wearing rocks, tool wear and tool circle consumption are fast, which seriously affects the TBM tunneling rate. Therefore, when rock hardness is low, the TBM tunneling rate is high; when rock hardness is high, the TBM tunneling rate is significantly reduced. However, when rock hardness is too low, the surrounding rock easily becomes unstable, which affects the TBM tunneling rate.

3D SIMULATION OF THE TBM ROCK-BREAKING PROCESS

The west route of the South-to-North Water Transfer Project, such as in the Niqu–Du Ke River water diversion line, according to the rock mechanical parameters used in the model selection of rock mechanical parameters obtained by rock test chamber, the TBM tool-breaking process simulation and analysis. The Niqu–Du Ke River water diversion line, which is located in the territories of Sichuan County in Ganzi Province and Rangtang County, is deeply buried into the long tunnel selection line of the main project. The average depth is generally 300–800 m; the maximum depth is 1190 m. The line area of the lithology of outcropping strata that are composed of Triassic metamorphic sandstone and slate, the degree of fracture development influenced by lithology, lithology, rock thickness, generally larger than sandstone slate, thin than thick layer, with an increase in depth, the degree of fracture development is weakened. In this study, the discrete element method 3DEC is used to simulate the rock-breaking process of TBM. The influence rule of rock mechanical parameters on the TBM tunneling rate is also determined.

BASIC ASSUMPTIONS IN ESTABLISHING THE 3D SIMULATION MODEL

To reasonably simulate the breaking force of TBM and the joints in a rock mass, certain parameters were assumed in the calculation of the discrete element. The joints are linear elastic materials. The rock materials did not swell when the surrounding rock was subjected to shear action. The cutter head and the cutter were assumed as linear elastic materials. An excavation area of 100 m x 100 m x 100 m was selected according to the influence of TBM excavation. To analyze the rock-breaking process of the TBM cutter, a smaller model (10 m x 10 m x 10 m) was used within the tunnel excavation scope. Figure 1 shows a 3D simulation of the TBM tunnel excavation model.

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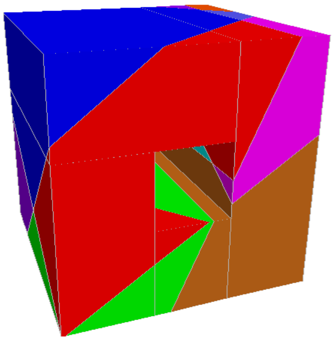

Fig. 1 - 3D simulation model of tunnel excavation using TBM

SELECTION OF ROCK MECHANICAL PARAMETERS

A total of 15 groups of rock mechanical parameters were selected from the experiment (Table 1). The joint spacing was assumed as 30 mm, with a joint and tunneling direction angle of 60°. The 3D simulation model of the TBM cutter rock-breaking process was established, which modified the rock mechanical parameters in the model for discrete element calculation and analysis.

Tab. 1 - Selected rock mechanical parameters

Group	Rock UCS/MPa	Elastic modulus/GPa	Poisson's ratio
1	31.5	13.3	0.51
2	33.1	15.7	0.46
3	43.6	23.6	0.45
4	45.7	30.1	0.43
5	51.6	35.3	0.38
6	55.7	39.1	0.35
7	58.3	41.2	0.29
8	67.3	43.5	0.26
9	78.5	46.5	0.22
10	92.7	47.5	0.21
11	101.5	49.3	0.21
12	105.6	51.2	0.18
13	107.1	60.3	0.16
14	111.3	71.8	0.16
15	117.0	84.1	0.15

Calculation formula for drilling rate:

$$V = 60Pn/1000 \tag{1}$$

$$T = 1800/Pn \tag{2}$$

$$N = 9000 \tag{3}$$

$$\omega = 4.5 \tag{4}$$

$$d = 4.53 \tag{5}$$

where V denotes the drilling rate, m/h; P indicates penetration, mm/r; n signifies the rotation rate of the cutter head, r/min; T is the drilling time of each route, mm/min; N is pressure at face, kN; ω is the rotation rate of the cutterhead, r/min; d is the cutterhead diameter, m.

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The difference in TBM penetration into rock depth under varying joint directions is obtained according to 3D simulation. The TBM tunnelling rate under different rock mechanical parameters is calculated using the formula.

Some of the 3DEC codes in the 3D simulation model of TBM penetration are as follows.

```
new
poly brick -35,35 -35,35 -50,50
jset dd 270 dip 60 origin 0.3,0,0
jset dd 230 dip 30 oeigin 0,0,-0.3
jset dd 320 dip 15 origin 0,0,0.3
plot hold dip 70 dd 200 color mat
ret
tunnel a (-16.3,-16.3,-30.5) (-16.3,16.3,-30.5) (16.3,16.3,-30.5) (16.3,-16.3,-30.5) &
    b (-16.3,-16.3,30.5) (-16.3,16.3,30.5) (16.3,16.3,30.5) (16.3,-16.3,30.5)
remove -16.3,16.3 -16.3,16.3 -30.5,30.5
plot hold dip 70 dd 200 color mat
plot hold exc joint
ret
gen edge 1.0
prop mat=1 dens 2630 bulk 1.5e7 g 0.7e8
prop mat=2 dens 2760 bulk 1.5e7 g 0.2e8
prop jmat=1 kn 1e9 ks 1e9 coh 1e9 ten 1e9
ret
bound -10,10 60,30 -10,10 stress 0.0 -1e6,0.0 0,0,0
bound -10,-60 -10,10 -10,10 xvel 0.0
bound 60,30 -10,10 -10,10 xvel 0.0
bound -10,-60 -10,10 -10,10 zvel 0.0
bound -10,-60 -10,10 60,30 zvel 0.0
bound -10,-60 -60,-30 -10,10 yvel 0.0
grav 0,-10,0
insitu stress -0.5e6 -1.5e6 -0.5e6 0 0 0
ret
hist unbal
hist ydis 30,30,0
hist ty 1
step 500
save tun0.sav
ret
```

```
rest tun0.sav
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ANALYSIS OF THE RELATIONSHIP BETWEEN ROCK MECHANICAL PARAMETERS AND THE TBM TUNNELING RATE

Rock mechanical parameters that affect the TBM tunnelling rate include rock UCS, elastic modulus, and Poisson's ratio. Within a certain range, when rock UCS is low, the TBM tunnelling rate is high; when rock UCS is high, the TBM tunnelling rate is low. However, when rock UCS is too low, the self-stability of the surrounding rock decreases, collapse can easily occur, and the TBM tunnelling rate is reduced. When TBM is driving into hard-wearing rocks, tool wear and tool circle consumption are fast, which seriously affects the TBM tunnelling rate. Therefore, when rock hardness is low, the TBM tunnelling rate is high; when rock hardness is high, the TBM tunnelling rate is low. However, when rock hardness is too low, the surrounding rock easily becomes unstable, which affects the TBM tunnelling rate. Table 2 presents the change in the TBM tunnelling rate with the rock mechanical parameters when the joint condition in the rock mass obtained by the 3D simulation calculation is constant. Figure 2 shows the relationship of the TBM tunnelling rate to rock UCS, elastic modulus, and Poisson's ratio.

Tab. 2 - Excavation rate of TBM change with rock mechanical parameters

TBM drilling rate/(m/h)	Triaxial compressive strength/MPa	Elastic modulus/GPa	Poisson's ratio
2.43	33.1	15.7	0.46
2.36	43.6	23.6	0.45
2.11	45.7	30.1	0.43
2.12	51.6	35.3	0.38
2.09	55.7	39.1	0.35
1.83	58.3	41.2	0.29
1.81	67.3	43.5	0.26
1.71	78.5	46.5	0.22
1.56	92.7	47.5	0.21
1.13	101.5	49.3	0.21
0.91	105.6	51.2	0.18
0.91	107.1	60.3	0.16
0.73	111.3	71.8	0.16
0.63	117	84.1	0.15

As shown in the Figure 2 to Figure 4, the TBM tunnelling rate decreases with an increase in rock UCS and elastic modulus within a certain range and increases with an increase in rock Poisson's ratio. The curves in Figures 2 and 3 are similar to the straight line with a negative slope, whereas the curve in Figure 4 is similar to the straight line with a positive slope. Therefore, the least squares method can be used to synthesize the three curves.

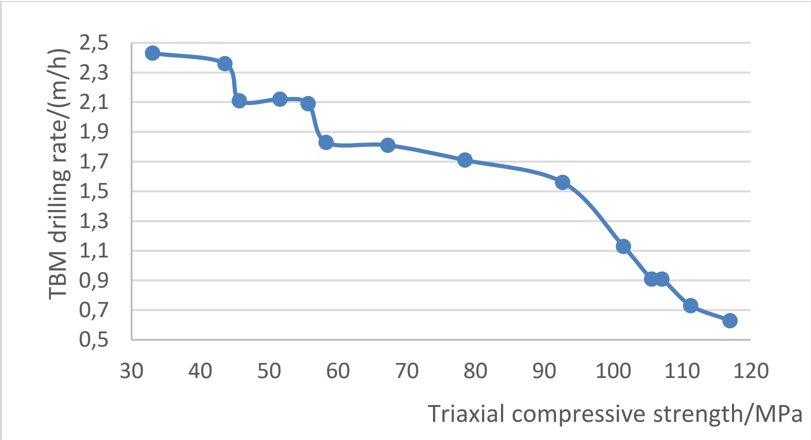

Fig. 2 - Relation diagram between the TBM driving rate and Triaxial compressive strength

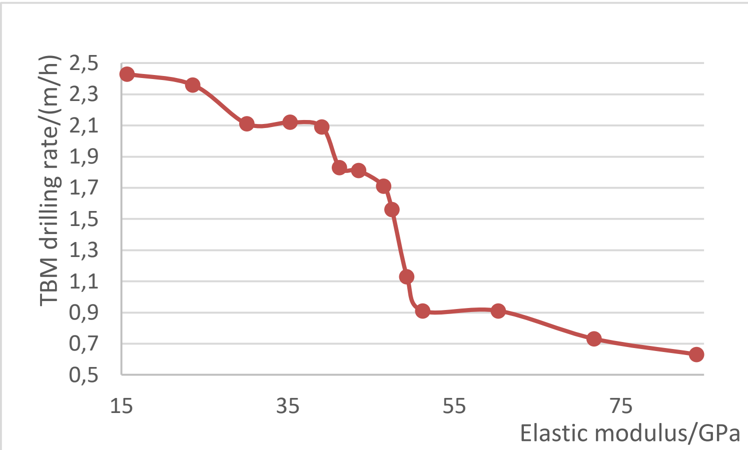

Fig. 3 - Relation diagram between the TBM driving rate and Elastic modulus

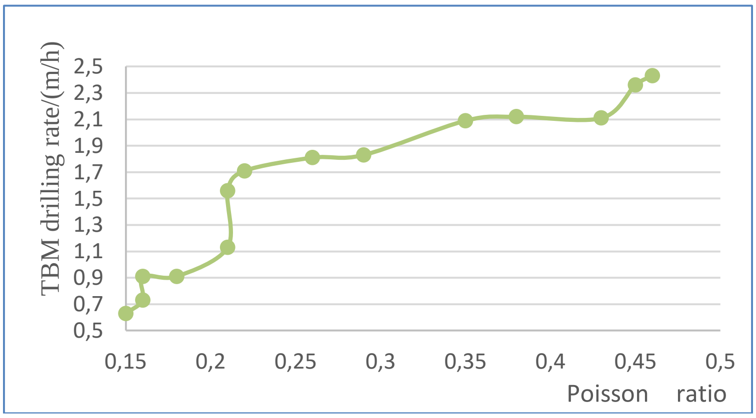

Fig. 4 - Relation diagram between the TBM driving rate and Poisson's ratio

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CONCLUSION

In the construction example of the west route of the South-to-North Water Transfer Project, the 3D discrete element method was used to simulate the rock-breaking process of a TBM hob, and the influences of rock mechanical parameters on the driving speed of TBM was analyzed. The following conclusions were obtained. The physical and mechanical properties of the surrounding rock in the tunnel influence the driving speed of the TBM. When the strength of the surrounding rock is low, the driving speed of TBM is high. When the strength of the surrounding rock is high, TBM tunnelling will experience difficulties, and driving speed will be reduced. The linear map of the relationship between the TBM driving rate and the rock mechanical parameters fitted using the least squares method is similar to the data obtained using the existing TBM construction monitoring method. Therefore, the analysis in this study can play a guiding role in the construction of the west route of the South-to-North Water Transfer Project.

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