Influence of in-situ stress on rock fragmentation by TBM cutters and prediction of TBM performance for deep tunnels

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Abstract. In-situ stress is a significant factor influencing TBM tunneling for deep tunnels, especially for the construction of deep repository for radioactive waste disposal. Beishan area of Gansu Province is the first preferred area for high-level radioactive waste disposal repository in China, and the feasibility of using TBM technology in Beishan area is investigated in recent years. In this paper, six levels of in-situ stress related to different depths from ground to 500m at Beishan area were selected and the influence of in-situ stress on rock fragmentation was investigated by linear cutting test. The rock samples were collected from the Jijicao site in Beishan area, with uniaxial compressive strength of 105.6MPa. The test results show that: 1) there is a clear power function correlation between the penetration and the normal cutter force for each stressed condition, and the higher the confining stress, the smaller the gradient of the power function curve, which means slower increase of penetration rate under the same cutterhead thrust; 2) the required normal cutter force increases with the increase of overburden as the corresponding in-situ stress increases. Based on the laboratory testing, the Specific Rock Mass Boreability Index model was modified and further used in the prediction of TBM performance at different depths on Jijicao site. This paper helps better understanding of rock fragmentation mechanism in TBM tunneling in stressed ground, and also provides reference on parameter selection for TBM operation in deep tunnel tunnelling.

1. Introduction
With its continuous development, TBM technology is extensively used in deep underground engineering due its notable advantages of fast advancing and less disturbance to the rock mass, especially for deep geological disposal projects for radioactive waste [1]. However, with its application in deep tunnels, TBMs have to deal with rock stress problems induced by overburden or anisotropic stresses. Therefore, it’s necessary to understand the influence of in-situ stress on TBM performance.

A lot of studies have been conducted on the TBM performance under stressed geological conditions. By field observation, Gehring [2] found that the cutter consumption for TBM tunneling under high overburden (800 m) was greater than that under lower overburden, likely due to the higher thrust required for TBM advance under higher stress condition. However, some other experiences [3, 4]...
revealed the positive effects of high stress on the TBM advance. By laboratory tests, Chen and Labuz\textsuperscript{5} described the transition of rock failure from brittle to ductile mechanism with increasing confining stress by wedge indentation test. Yin et al. \textsuperscript{6} concluded that the force for crack initiation and the size of the crushed zone under TBM cutter increased with the increase of the confining stress by using indentation test and AE technology. Ma et al. \textsuperscript{7} and Pan et al. \textsuperscript{8} demonstrated the significance influence of confining stress on cutter penetration by using linear cutting test. By using numerical method, the rock fragmentation mechanism during the cutter indentation process and the TBM performance under stressed condition were investigated by many researchers \textsuperscript{9, 10}. The investigations above provided further understanding on TBM tunneling the in-situ stressed condition. However, it failed to present systematical investigation on real in-situ conditions. Full-scale rock cutting experiments, such as the linear cutting test, have been proved to be reliable for prediction of TBM performance \textsuperscript{7, 11, 12}. This approach uses full-scale rock specimens and cutting tools, and allows a realistic range of cutting loads to be applied. Therefore, the results derived from the test can be directly applied to prediction of field performance \textsuperscript{12}. For the prediction models of TBM performance, there are generally two categories of models developed in the past decades: one is the theoretical model, and the other empirical model. A summary of advantages and disadvantages of these model concepts are discussed by Rostami \textsuperscript{13}. Specific rock mass boreability index (SRMBI) \textsuperscript{14} is an excellent compendium of TBM performance prediction models \textsuperscript{13}. The index combines the cutting force analysis and correlation analysis between the actual penetration rate and rock mass parameters. It is proposed for the penetration rate prediction based on the rock breakage process analysis, and it can also be used to evaluate the rock mass boreability. However, most of the available models have failed to take in-situ stress into account.

On the base of previous tests by Ma et al. \textsuperscript{7}, two more linear cutting tests were conducted in this paper. The effect of in-situ stress at different depths in the Beishan area on TBM performance was discussed. Furthermore, the modified SRMBI model was proposed by considering the factor of in-situ stress on the base of cutting test, and then used to predict the TBM performance for deep geological disposal project at Beishan site.

2. Test design and results

2.1 Test design

Six levels of depth-related stress condition were investigated in this paper. Based on the in-situ stress distribution in the Beishan area \textsuperscript{15}, the stress condition at the tunnel face of different overburden from ground to 500m can be obtained by the FLAC\textsuperscript{10} numerical simulation. The confining stress parameters $\sigma_y, \sigma_z$ in linear cutting tests are then determined according to the numerical results, as shown in table1. $\sigma_y$ represents the stress in the direction parallel to the cutting direction, while $\sigma_z$ perpendicular to the cutting direction.

Based on the field experience, the constant-cross section disc cutter with diameter of 432 mm (17-inch) and cutter spacing of 80 mm are adopted, and the range of penetration is 0.5–4.0 mm with the interval of 0.5mm, as listed in table 1. The mechanical rock breakage experimental platform and the granite rock samples for linear cutting tests are shown in figure 1 and figure 2. The samples were collected from the Jijicao site in the Beishan area of Gansu Province, China, with the two kinds of sizes of 980mm×980mm×600mm and 780mm×780mm×500mm, which are large enough to avoid scaling effect. The former four sets of cutting tests were conducted in previous work\textsuperscript{7}, the last two sets with higher confining stress were conducted in this paper. The physical and mechanical parameters of Jijicao granite rock are listed in table 2.

2.2 Test results

For each penetration depth, cutting of 5–8 layers (or passes) were performed to ensure the collected data was valid. The results of the average normal force $F_n$ are obtained, as shown in table 3. The average force is the average value of all the valid data collected from tests of the same penetration
depth, which means collecting all the instant and valid records of normal force of every cutting layer for the same penetration by the data acquisition system, and then average these data.

### Table 1. Test design parameters.

| No. | Sample dimension (mm) | Confining stress $\sigma_x, \sigma_y$ (MPa) | Overbuden (m) | Penetration $P$ (mm) |
|-----|-----------------------|---------------------------------|--------------|-------------------|
| 1   | 980×980×600           | 0_0                             | 0            | 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 |
| 2   | 980×980×600           | 5_10                            | 100          | 0.5, 1.0, 1.5, 2.0, 2.5 |
| 3   | 980×980×600           | 10_10                           | 200          | 0.5, 1.0, 1.5, 2.0, 2.5 |
| 4   | 980×980×600           | 15_15                           | 300          | 0.5, 1.0, 1.5, 2.0, 2.5 |
| 5   | 780×780×500           | 15_20                           | 400          | 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 |
| 6   | 780×780×500           | 20_23                           | 500          | 1.0, 2.0, 2.5, 3.0, 3.5, 4.0 |

### Table 2. Physical and mechanical properties of the Beishan granite samples.

| Density $\rho$ (g/cm$^3$) | Young's modulus $E$ (GPa) | Poisson's ratio $\nu$ | Uniaxial compressive strength UCS (MPa) | Braialian tensile strength (MPa) |
|---------------------------|---------------------------|-----------------------|----------------------------------------|---------------------------------|
| 2.60                      | 23.02                     | 0.188                 | 105.6                                  | 6.4                             |

**Figure 1.** The mechanical rock breakage experimental platform.  
**Figure 2.** Some of the granite rock samples.

### Table 3. Summary of test results under different confining stressed conditions.

| Penetration $P$ (mm) | Normal force $F_n$ (kN) |
|----------------------|--------------------------|
|                      | $H=0$m: $5_{10}$ MPa | $H=100$m: $5_{10}$ MPa | $H=200$m: $10_{10}$ MPa | $H=300$m: $15_{15}$ MPa | $H=400$m: $15_{20}$ MPa | $H=500$m: $20_{23}$ MPa |
| 0.5                  | 96.6                     | 105.5                  | 108.1                   | 115.2                   | 118.8                   | -                         |
| 1.0                  | 126.2                    | 131.7                  | 140.3                   | 151.3                   | 162.8                   | 179.6                     |
| 1.5                  | 148.7                    | 164.4                  | 160.7                   | 169                     | 185.9                   | -                         |
| 2.0                  | 174.2                    | 183.6                  | 190.6                   | 198.6                   | 207.4                   | 235.4                     |
| 2.5                  | 197.6                    | 207.5                  | 207.6                   | 216.5                   | 223.2                   | 264.8                     |
| 3.0                  | 210.4                    | -                      | -                       | -                       | 246.9                   | 280.4                     |
3. Influence of in-situ stress on rock fragmentation by TBM cutters

3.1 Influence of depth-related stress on Normal Force $F_n$

Normal force determines the thrust requirement. Moreover, since rock cutting by roller disk cutters is in fact an indentation process, the normal force dominates the rock fragmentation. Under a certain cutterhead rotation speed, the penetration per revolution (PRR) in field can be equivalent to the penetration depth in the linear cutting test. Thus, the relationship of normal force and penetration subjected to different confining stresses by cutting tests (figure 3) is investigated, in order to evaluate the effect of confining stress on TBM penetration rate on site.

As shown in figure 3, with the increase of confining stress, the normal force increases when the same penetration is reached. For instance, when the penetration is 1.0 mm, the normal force applied under the confining stress condition of $\sigma_x, \sigma_y=20, 23$ MPa is increased by 42.3%, 28.0%, 10.3%, respectively, when compared to the confining stressed conditions of 0 MPa, 10, 10 MPa, 15, 20 MPa accordingly. The reason is that the fracture initiation and propagation in rock samples is limited and the rock resistance strength is improved by the enhancement of confining stress, which makes rock fragmentation more difficult. This conclusion is consistent with the results of the indentation test provided by Chen and Labuz [5] and Yin et al. [6].

By nonlinear fitting analysis, it is found that there is a good power function correlation between the penetration $P$ and the normal force $F_n$ for each stressed condition, and there also exists a critical point. Only if the normal force is larger than the critical force, the penetration increases rapidly. The result agrees with the in situ penetration test conducted at Jinping II Hydropower Station [4]. It can also be found that, the higher the confining stress, the smaller the gradient of the power function curve. It means the higher confining stressed condition results in slower increase of penetration rate under the same cutterhead thrust, mainly due to crack initiation strength enhanced rapidly by stronger confining limitation. Therefore, much higher thrust is required for effective fragmentation under higher stressed condition. However, it should be noted that the increase of thrust will lead to rapid cutter wear at the same time.

![Figure 3](image_url)  
**Figure 3.** The relationship of normal force and penetration under different conditions.
depth-related stress conditions.

According to the in-situ stress in Beishan area, the figure 3 shows the relationship between normal cutter force and penetration at different depth from ground to 500 m. The normal force increases with the depth, and the required increments of normal force is higher when the overburden goes deeper every 100 m. To reach the penetration of 2.5 mm, the normal force required at the depth of 500 m is increased by 34.0% and 18.6% respectively, when compared with that of depths of 0 m and 400 m.

3.2 Influence of depth-related stress on rock mass boreability

Specific rock mass boreability index (SRMBI) $BI_{(1)}$ \cite{14} is defined as the normalized cutter force at the penetration rate of 1 mm per revolution. The lower is the $BI_{(1)}$, the higher is the rock boreability. Generally, the $BI_{(1)}$ can be obtained by in-situ TBM penetration test. In this paper, the $BI_{(1)}$ was calculated based on the cutting test results. It should be noted that, the factors of in-situ stress and cutter parameters are not considered in the index of $BI_{(1)}$, here the $BI_{(1)c}$ is defined as the specific rock mass boreability index with considering these two type factors. As shown in figure 4, a good relationship of power function can be found between rock boreability index $BI$ and penetration $P$, and expressed by the form of equation (1):

$$BI = BI_{(1)c} P^b$$

where $BI$ is rock boreability index, defined as the cutter force per mm, $BI_{(1)c}$ is the specific rock mass boreability index with considering the cutter parameters and in-situ stress, $P$ is the penetration per revolution, $b$ is the power constant of the power function.

For different depths of 0 m, 100 m, 200 m, 300 m, 400 m and 500 m, the corresponding $BI_{(1)c}$ value are $128.48$, $137.81$, $141.32$, $149.94$, $158.37$, $180.81$ kN/cutter/(mm/r) respectively. Compared with that at depth of 0 m, the $BI_{(1)c}$ value of depth of 500 m increases 40.7%. Figure 5 shows the relationship of $BI_{(1)c}$ and depth. With the increase of depth $H$, the $BI_{(1)c}$ increases as quadratic function, which means the rock mass boreability reduces dramatically at deep overburden.

![Figure 4. Rock mass boreability under different depth-related stress conditions.](image-url)
4. Modified SRMBI model by linear cutting test
Specific rock mass boreability index (SRMBI) [14] can be expressed by a power function of four parameters, i.e., rock uniaxial compressive strength (UCS), rock brittleness index (\(B_i\)), joint spacing (\(J_v\)) and joint orientation (\(\alpha\)), as shown in equation (2):

\[
 BI_{(1)} = 37.06 \cdot UCS^{0.26} \cdot Bi^{0.10} \cdot (0.84e^{0.051v} + e^{0.09} \sin(\alpha+30^\circ))
\]

(2)

where \(BI_{(1)}\) is the SRMBI index, \(B_i\) is the ratio of UCS to tensile strength.

The equation (2) is established based on the specific cutter parameters, i.e., cutter shape, cutter spacing. In addition, the model does not take the in-situ stress into account; however the effect of in-situ stress should not be neglected for deep tunnels. As stated in Section 3.2, \(BI_{(1)dc}\) is defined as the specific rock mass boreability index with considering cutter parameters and in-situ stress. For the specific cutter parameters used in the cutting test and the in-situ stress condition of Beishan area, \(BI_{(1)dc}\) is the fitting function as shown in figure 5, i.e., \(BI_{(1)dc} = 0.0002H^2 + 0.0189H + 130.83\). Derived from this type of function, the \(BI_{(1)dc}\) can be expressed in equation (3):

\[
 BI_{(1)dc} = f(H) + k \cdot BI_{(1)}
\]

(3)

where \(BI_{(1)dc}\) is specific rock mass boreability index with considering the TBM parameters and in-situ stress; \(f(H)\) is the function related to the in-situ stress, \(H\) is the tunnel depth, and particularly for in-situ condition of Beishan area, \(f(H) = 0.0002H^2 + 0.0189H\); \(k\) is the correction factor related to the cutter shape and cutter spacing, particular for the cutter parameters used in cutting test in Section 2.1, \(k=1\).

Then, the required cutter normal force \(F_n\) for different depths can be modified as equation (4):

\[
 F_n = BI_{(1)dc} \cdot P^{b} \cdot P = (f(H) + k \cdot 37.06 \cdot UCS^{0.26} \cdot Bi^{0.10} \cdot (0.84e^{0.051v} + e^{0.09} \sin(\alpha+30^\circ))) \cdot F^{b} \cdot P
\]

(4)

where \(F_n\) is the required cutter normal force to reach the penetration \(P\) at the tunnel depth \(H\).

5. Prediction of TBM performance for Jijicao site
For the prediction of TBM performance for Jijicao site in Beishan area, and if the same cutter shape and cutter spacing are selected as used for linear cutting tests in section 2.1, then \(f(H) = 0.0002H^2 + 0.0189H\), the correction factor \(k=1\), and the power constant \(b\) related to different depths can be obtained by fitted power functions in figure 4. The The rock strength parameters (UCS, \(B_i\)) at different depths are obtained by mechanical tests on borehole cores and listed in table 4. As the rock mass of Jijicao site is of high integrity with little fractures, it is assumed \(J_v=0\), \(\alpha=0\). By using the modified
SRMBI model, the cutter forces required to reach different penetrations at different depths for Jijicao site can be calculated. The results are listed in Table 4 and shown in Figure 6. Within the maximum capacity for 17-inch cutter as 267kN, the maximum penetration can be predicted for different depths. The results demonstrate that, the penetration of 4mm and 2mm can be reached at depth of 300m and 500m respectively for 17-inch cutter.

Table 4. Prediction results of the required cutter normal force at different depths.

| Depth H (m) | UCS (MPa) | Bi | Fc (kN) |
|-------------|-----------|----|---------|
|              |           |    | P=1.0mm | P=2.0mm | P=3.0mm | P=4.0mm | P=5.0mm |
| 100         | 117.85    | 16.84 | 135.68 | 181.91 | 215.95 | 243.9 | 268.03 |
| 200         | 123.46    | 11.84 | 150.53 | 199.45 | 235.13 | 264.27 | 289.33 |
| 300         | 107.21    | 12.21 | 156.15 | 204.34 | 239.15 | 267.39 | 291.58 |
| 400         | 152.77    | 12.59 | 179.93 | 235.62 | 275.88 | 308.54 | 336.52 |
| 500         | 155.76    | 13.64 | 196.39 | 257.52 | 301.76 | 337.69 | 368.47 |

Figure 6. The relationship of required cutter force and depths with different penetrations.

6. Conclusions
The influence of in-situ stress on TBM performance for deep tunnels was investigated by linear cutting tests, and the result was used to modify the SRMBI model for performance prediction of deep tunnel excavation. The main conclusions can be summarized as following:

(1) The linear cutting test for the Jijicao rock samples show that, the required normal force increases with the increase of overburden. For the penetration of 2.5mm, the required normal force at the depth of -500m is increased by 34.0% and 18.6% respectively, when compared with the depths of 0m and 400m.

(2) The prediction of penetration rate of the Jijicao rock mass is conducted by the modified SRMBI model. The results show that, the penetration of 4mm and 2mm can be reached at depth of 300m and
500m respectively for 17-inch cutter. The results provide reference for optimization of TBM design and operational parameter for this specific site.

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