Experimental investigation of rock cuttability based on rock indentation tests by a conical pick

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Abstract. Stress conditions and rock properties significantly influence rock breakage. The rock indentation tests by a conical pick were conducted to investigate the rock cuttability correlated to confining stress conditions and rock strengths. Based on the test results, the regression analyses were used to find the relationship among rock cuttability, uniaxial confining stress applied to rock, uniaxial compressive strength (UCS) and tensile strength of rock material. It was found that the regression models can accurately reflect the variation law of rock cuttability, which presents decreases followed by increases with increases in uniaxial confining stress and the negative correlation to UCS and tensile strength of rock material. The established models are suitable for guiding the rock cutting by conical pick and will provide useful information for mechanized mining in deep hard rock.

1. Introduction
Mechanized excavation is a widely used method in rock engineering, which can be as an alternative approach to drilling and blasting method, benefiting from its numerous advantages: continuous and safe operation, high quality of construction and low excavation disturbance[1,2]. Rock cuttability is a comprehensive parameter reflecting the interaction between cutter and rock, which can be defined as the easiness of rock breakage by cutter and determines the feasibility of mechanized excavation. Rock cuttability is influenced by rock properties and stress conditions[3]. Mechanized excavation method has been widely used in soft and medium-hard rock, such as coal, bauxite and salt minerals, while it is unsuitable for extremely hard rock[4]. The mining operations now exist with depths exceeding 4 km, and deep mining of non-ferrous metals at depths greater than 1 km is often in hard rock mines[5]. Therefore, the application of mechanized excavation in hard rock is an urgent problem and should be addressed in...
Deep mining. High stress is a prominent condition in rock around deep opening, which had been traditionally considered as a disaster factor to induce instability and dynamic failure of rock, such as rockburst, large deformation, slabbing and zonal disintegration\[^6,7\].

Many previous efforts had been taken to study the rock cuttability. In experimental investigations, the multiform approaches had been undertaken, which included full-scale and small-scale cutting experiments, linear and rotary cutting tests, single- and multi-cutters cutting tests, and so on. These experimental investigations were taken to investigate the cutting force, cutting work, specific energy, fragment yield, shape and size of fragments, fractured surface roughness and wear of cutter under different conditions of rock properties and cutting operations\[^8-15\]. In terms of theoretical models, some analytical and semi-empirical expressions had been proposed to determine the peak cutting force of conical cutter\[^16-20\]. For numerical simulations, the finite element method (FEM), discrete element method (DEM) and coupled FEM-DEM method had been used to simulate the rock fragmentation by conical or point-attack cutters to trace the complex fracturing process and reduce costs\[^21-23\]. The valuable studies mentioned above had played a significant role in understanding rock cuttability and cutting performances under different rock properties and cutting parameters. However, the previous efforts did consider the influences of confining stress condition that can be ignored in shallow excavations but is a common factor in deep mining and tunnelling\[^3\].

In this paper, the rock indentation tests by a conical pick under the different uniaxial confining stress conditions were conducted on the granite, marble, red sandstone and phosphate rocks by using the true-triaxial loading system. The peak indentation force of conical pick for rock breakage were used to assess the rock cuttability. Then, the two- and three-dimensional regression analyses were used to establish the relationship models of rock cuttability correlated with the confining stress conditions and rock strength properties.

2. Rock indentation experiments

2.1. Experimental apparatus

The rock indentation experiments were performed with TRW-3000 true triaxial electro-hydraulic servo test system shown in Figure 1, which was designed and manufactured by Central South University. This system can perform rock loading tests under triaxial stress conditions. The maximum static loads in the \(X\)-, \(Y\)- and \(Z\)-directions can reach 2000 kN, 2000 kN and 3000 kN, respectively.

2.2. Rock specimens

The granite, marble, red sandstone and phosphate rock specimens were selected in rock indentation experiments, which were all cubic rock specimens with size of 100×100×100 mm. There were 35 groups of rock specimens, including 9 groups of granites, 9 groups of marbles, 8 groups of red sandstones, and 9 groups of phosphate rocks. The uniaxial compressive strength (UCS) and tensile strength of rock materials were listed in Table 1.
Figure 1. TRW-3000 true triaxial electro-hydraulic servo system for true triaxial loading test, which includes (a) true triaxial loading system and (b) loading frame of rock indentation by a conical pick.

Table 1. Strengths of rock materials used in the tests.

| Rock material     | Uniaxial compressive strength $\sigma_c$ (MPa) | Tensile strength $\sigma_t$ (MPa) |
|-------------------|-----------------------------------------------|----------------------------------|
| Granite           | 126.24                                        | 7.56                             |
| Marble            | 129.22                                        | 6.18                             |
| Red sandstone     | 97.79                                         | 5.31                             |
| Phosphate rock    | 106.21                                        | 5.24                             |

2.3. Experimental processes

In order to simulate the rock breakage on pillar by conical picks mounted on the mining machine such as roadheader, the rock indentation tests were conducted on cubic rock specimens, which were subjected to uniaxial confining stress on a pair of lateral end faces and broken by a conical pick, as shown in Figure 2. The loading frame is shown in Figure 2b. Firstly, the uniaxial confining stress was applied to the left and right lateral end faces of rock specimen by $Y$-direction loading. Then, a concentrated force was applied to a conical pick by $Z$-direction loading until rock breakage.

Figure 2. Loading condition for simulating rock indentation on pillar by conical pick, which includes (a) schematic mining process for cutting pillar and (b) simplified loading platform.

In the rock indentation tests, the 9 groups of granite rock specimens and the 9 groups of marble rock specimen were tested under uniaxial confining stresses of 5, 10, 20, 40, 60, 80, 100, 120 MPa and stress-free condition (0 MPa), respectively. The 8 groups of red sandstone rock specimens were tested under uniaxial confining stress of 5, 10, 20, 40, 60, 80, 90 MPa and stress-free condition (0 MPa), respectively.
The 9 groups of phosphate rock specimens were tested under uniaxial confining stress of 5, 10, 20, 40, 60, 80, 90, 100 MPa and stress-free condition (0 MPa), respectively.

The indentation forces can be directly fed back to the computer through the load monitoring sensors during tests. The peak indentation force at rock failure can be extracted from the real-time monitoring data of the indentation force of conical pick. The rock cuttability can be reflected by peak indentation force, and the low value of this index indicates the good rock cuttability.

3. Regression analyses of experimental results

3.1. Two-dimensional regression

The four models were regressed by experimental results, which were expressed as Eqs. (1)-(4) to reflect the peak indentation forces of conical pick for breakages of granite, marble, red sandstone and phosphate rock specimens under different uniaxial confining stresses, respectively. The regressive curves were plotted in Figure 3. By analyzing the experimental and regressive results and the failure patterns, the variation trend of peak indentation force can be divided into three zones. In the Zone 1 with uniaxial confining stress varying from 0 to the level near 30%-40% of UCS of rock material, there was a positive correlation in which the peak indentation force increased with increases in uniaxial confining stresses, and the failure pattern was complete splitting. In the Zone 2 with the uniaxial confining stress varying from the level near 30%-40% of UCS of rock material to the level near 80% of UCS of rock material, there was a negative correlation in which the peak indentation force decreased with the increases of the uniaxial confining stresses, and the failure pattern of rock was partial splitting. In the Zone 3 with uniaxial confining stress exceeding the level near 80% of UCS of rock material, the peak indentation force continued to decrease, and the rockburst occurred.

\[ F_c = 44.7(0.03661\sigma^2 e^{-0.2164\sigma^{0.7}} + 1) \]  
\[ F_c = 23.81(0.0768\sigma^2 e^{-0.2056\sigma^{0.7}} + 1) \]  
\[ F_c = 13.04(0.05553\sigma^2 e^{-0.06109\sigma} + 1) \]  
\[ F_c = 10.49(0.002582\sigma^4 e^{-0.4695\sigma^{0.7}} + 1) \]  

where \( F_c \) is the peak indentation force, and \( \sigma \) is the uniaxial confining stress.

In order to evaluate the reliabilities of regression models, we evaluated each model using the root-mean-squared error (RMSE) and goodness of fit (\( R^2 \)) expressed as Eq. (5) and Eq. (6), respectively. The corresponding RMSE and \( R^2 \) values were obtained and listed in Table 2.

\[ RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_{t(i)} - y_{p(i)})^2} \]  
\[ R^2 = \frac{\sum_{i=1}^{n} (y_{p(i)} - \bar{y}_t)^2}{\sum_{i=1}^{n} (y_{t(i)} - \bar{y}_t)^2} \]

where \( y_{t(i)} \) is the experimental value, \( y_{p(i)} \) is the regression value, \( \bar{y}_t \) is the mean of all experimental values, and \( n \) is the number of values.
Table 2. RMSE and $R^2$ values of two-dimensional fitting models for different rock types.

| Rock types       | RMSE (kN) | $R^2$ |
|------------------|-----------|-------|
| Granite          | 21.33     | 0.8717|
| Marble           | 13.37     | 0.9564|
| Red sandstone    | 7.29      | 0.9539|
| Phosphate rock   | 6.66      | 0.9786|

Figure 3. Regressed curves of peak indentation forces of conical pick for breakages of granite, marble, red sandstone and phosphate rock specimens under different uniaxial confining stresses.

3.2. Three-dimensional regression

In order to characterize the influences of rock properties and uniaxial confining stress conditions on the rock cuttability reflected by peak indentation force, the three-dimensional regression analyses were taken by the experimental data obtained from rock indentation tests. The UCS and tensile strength of rock material were used to determine rock properties.

The USCs of granite, marble, red sandstone and phosphate rock materials were taken as the $X$-axis, the different uniaxial confining stresses applied to rock specimens were taken as the $Y$-axis, and the peak indentation forces applied to conical pick for rock breakages were taken as the $Z$-axis. The curved surface was obtained by three-dimensional regression to express the relationship among peak indentation forces, USCs of rock materials and uniaxial confining stresses, the expression and illustration of which were shown in Eq. (7) and Figure 4, respectively. The products of USCs and tensile strengths was taken as the $X$-axis, but keep the $Y$-axis and $Z$-axis parameters unchanged. Another curved surface was achieved, we expressed it as Eq. (8) and Figure 5.
\[ F_c = 5.904 \times 10^{-5} \sigma_c^{2.2} \sigma_y^{2} e^{-1.771 \sigma_y^{0.4}} + 1 \]  
(7)

\[ F_c = 28.51 \times 10^{-8} \sigma_c^{2.2} \sigma_c^{2} \sigma_y^{2} e^{-1.758 \sigma_y^{0.4}} + 1 \]  
(8)

where \( \sigma_c \) and \( \sigma_t \) are the UCS and tensile strength of rock material.

Figure 4. Regressed curved surface of peak indentation force correlated to UCS of rock material and uniaxial confining stress, including (a) three-dimensional view of curved surface and (b) view of curved surface from X-axis.

Figure 5. Regressed curved surface of peak indentation force correlated with the product of UCS and tensile strength and the uniaxial confining stress, including (a) three-dimensional view of regressed curved surface and (b) view of regressed curved surface from X-axis.

Similar to the evaluation of two-dimensional regression model, RMSE and \( R^2 \) of three-dimensional model were obtained as shown in Table 3.

| Regression types | RMSE (kN) | \( R^2 \) |
|------------------|-----------|-----------|
| \( X \)-axis is UCS of rock material | 23.95 | 0.8473 |
| \( X \)-axis is the product of UCS and tensile strength of rock material | 26.96 | 0.8065 |

4. Conclusions

In this study, the rock indentation tests by a conical pick were performed on the granite, marble, red sandstone and phosphate rocks under the different uniaxial confining stress conditions to investigate the rock cuttability correlated to confining stress conditions and rock strengths. Then, the two- and three-
Dimensional regressions were used to establish the models to reveal the relationship of rock cuttability correlated with uniaxial confining stress applied to rock, UCS and tensile strength of rock material. The following conclusions can be drawn:

(a) The regression models can formulaically reflect the relationship of peak indentation force with the uniaxial confining stress applied to rock and the UCS and tensile strength of rock. The regression models are satisfactory for predicting the rock cuttability that can be reflected by peak indentation force of conical pick for rock breakage in the rock indentation test.

(b) The experimental results and regressive analyses indicated that the peak indentation force of conical pick for rock breakage presented increases followed by decreases with increases in uniaxial confining stress, and this index positively correlated to UCSs and tensile strengths of rock materials. The rocks under stress-free condition and low uniaxial confining stress can be cut efficiently and safely, while the rock under high uniaxial confining stress will occur rockburst, although the rock cuttability can be improved by high stress. Therefore, the rocks under stress-free and low confining stress have the best rock cuttability and cutting safety.

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