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A New Index For Evaluation Of Rock Brittleness

Ghadernejad S.[1], Lalegani Dezaki S.[2], Nejati H.R.[3*], Alipenhani B.[4]

1- M.Sc, Dept. of Mining Engineering, University of Tehran, Tehran
saleh.ghadernejad@ut.ac.ir
2- M.Sc, Dept. of Mining Engineering, University of Tehran, Tehran
saeed.lalegani@ut.ac.ir
3- Assistant Professor, Dept. of Rock Mechanics Engineering, Tarbiat Modares University, Tehran
h.nejati@modares.ac.ir
4- M.Sc, Dept. of Mining Engineering, University of Tehran, Tehran
b.alipenhani@ut.ac.ir

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Abstract: In the recent decades, the study of rock brittleness in infrastructure projects was addressed by different researchers. Unfortunately, a universally accepted definition of rock brittleness has not been presented yet. Furthermore, due to the lack of access to the equipment required and complexity and time consuming of the preparation and testing procedures of direct measuring of rock brittleness, indirect indices were mainly carried out. One of the most important Brittleness Indices, which has been widely used in various rock mechanic projects, is strength based brittleness index. The main objective of this study is to provide a new index on the basis of uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) for evaluating the rock brittleness. For this purpose, by reviewing the existing strength-based indices, a general equation was firstly suggested for the new index. Then, an integrated approach based on the statistical analysis and probabilistic simulation was applied in order to calculate the coefficients of suggested index. According to the obtained results, the values of 0.807 and 0.485 were proposed for UCS and BTS coefficients, respectively. Using the suggested index, it is possible to predict the rock brittleness with the value of R2 equal to 0.88.

Keywords: Rock brittleness, Punch penetration test, Uniaxial compressive strength (UCS), Tensile strength (BTS).

INTRODUCTION

Brittleness is one of the most important properties of rocks, which plays a significant role in the failure process of the intact rock. In the past half-century, various researchers have attempted to provide a clear and concise definition of rock brittleness. Morely defined brittleness as the lack of ductility [1]. Obert and Duval defined brittleness as a property of materials like cast iron and many rocks, which are fractured in just a little higher stress than their yield stress level [2]. Ramsay defined brittleness as *"when the internal cohesion of rock materials which are deforming in their elastic range is broken, the rocks are said to be brittle"* [3]. In addition, a wide range of definitions, less and more similar to the above-discussed definitions, have been suggested by different researchers.

Nowadays, due to the lack of a universally accepted definition for rock brittleness, a wide range of methods have been developed. The existing methods can be categorized into two distinct groups, including direct and indirect rock brittleness measurement methods. Yagiz introduced a new direct method based on the punch penetration test. He defined brittleness as the ratio of maximum applied force on the rock in kN to the corresponding penetration in mm [4]. This method has not been widely used that is due to not only the complexity and time consuming of rock preparations and test procedure but also the lack of access to the requiring equipment.

For the sake of simplicity, a wide range of indirect methods have been suggested by different researchers. Meng et al. classified the existing brittleness indices into two different groups, including indices derived from strain – stress curve and from physical-mechanical properties of rock [5]. Literature review revealed that among different indices, strength-based ones have been widely applied in different geo-engineering issues. The used brittleness indexes in this study are given below:

$$BI_1 = \left(\sigma_c / \sigma_t\right) \tag{1}$$

$$BI_2 = \left(\sigma_c - \sigma_t\right) / \left(\sigma_c + \sigma_t\right) \tag{2}$$

$$BI_3 = \left(\sigma_c \times \sigma_t\right) / 2 \tag{3}$$

$$BI_4 = \left(\sigma_c \times \sigma_t\right)^{0.72} \tag{4}$$

where σ_c is uniaxial compressive strength and σ_t is Brazilian tensile strength of rocks.

Strength-based indices have been widely utilized for assessment of different geo-engineering problems. In what follows, a brief review on the recent application of rock brittleness is presented. Ghadernejad et al. claimed that the rate of drilling has a significant and meaningful correlation with B4 [6]. Heidari et al. showed that there is no correlation between rock brittleness and porosity in both dry and saturated rocks [7]. Nejati and Moosavi stated that the rock fracture toughness can be predicted by B4 with high accuracy [8]. Young Ko et al. studied the effects of rock brittleness index on Cerchar abrasiveness index (CAI). They claimed that B3 and B1 have the highest impact on the CAI in metamorphic and igneous rocks, respectively [9]. Mikaeil et al. investigated the relationship between various strength-based brittleness indices and energy consumption in rock sawing process. The results showed that, B4 has the highest ability in prediction of the amount of used energy [10]. More recently, Mikaeil et al. utilized rock brittleness in order to predict the rate of penetration of tunnel boring machines [11].

NEW BRITTLENESS INDEX

To develop a new brittleness index, an open access dataset presented by Yagiz [4] was applied. The summary of dataset utilized is given in Table 1. After reviewing different indices (Equations 1-4), the below form was selected as the new brittleness index.

Table 1. Summary of open access dataset [4]

No	Rock type	Rock name	UCS (MPa)	BTS (MPa)	BI (KN/mm)
1	Sedimentary	Sandstone	120	6.2	30.5
2	Sedimentary	Limestone	141	6.7	35.0
3	Sedimentary	Sandstone	21	2.3	10.7
…	…	…	…	…	…
…	…	…	…	…	…
…	…	…	…	…	…
46	Igneous	Granite	315	17.8	41.0
47	Igneous	Granitoid	327	17.2	45.0
48	Igneous	Granite	165	8.9	32.0

In equation 5, *a* and *b* are the coefficients of UCS and BTS of rocks, respectively. In fact, the main aim of this study was to find the optimum coefficient for the proposed equation. In order to reach this goal, an integrated approach based on statistical analysis and probabilistic simulation has been applied. In what follows, the main procedure of utilized approach is discussed.

$$BI_n = \sigma_c{}^a \times \sigma_t{}^b \quad (5)$$

In the first step, multiple linear regression analysis between measured brittleness index (BIm) and UCS and BTS, was performed. The validation of the equation 6 was carried out by considering the determination coefficient, the t-test and F-test. The statistical results of the model are given in Table 2. Based on the multiple linear regression analysis, equation 6 can be suggested for the estimation of measured brittleness index:

$$BI_m = 0.201 \times UCS - 1.942 \times BTS + 17.05 \qquad R^2 = 0.86 \quad (6)$$

Table 2. Statistical result of the multiple regression model

Model	parameter	Coefficient	Std error	F-ratio	tab F-ratio	t-value	tab t-value
Eq. (6)	Constant	17.05	1.369	134.3	5.18	12.458	2.74
	UCS	0.201	0.017			11.735	
	BTS	-1.942	0.354			-5.488	

The statistical analysis has been carried out on a limited dataset, and generalization of the obtained results to other data may lay in unreliable estimations. To overcome this problem, the application of probabilistic simulation can be useful. In the second step, in order to determine the coefficient of proposed brittleness equation (equation 5), probabilistic analysis was utilized. In other words, this approach is applied in order to assess the impact of the input parameters on the output.

The probabilistic analysis is based on the generation of multiple attempts to calculate the expected values for a random variable. In this method, unlike the statistical analysis, distribution functions are utilized in order to define the input and output parameters. The distribution functions for input parameters were obtained based on the variation in parameters and Monte Carlo simulation was utilized to define the output distribution function. In this research, by utilizing the Monte Carlo simulation the impact of two normal distribution function (representing UCS and BTS) on measured rock brittleness has been determined. The input distribution functions are illustrated in Figures 1 and 2.

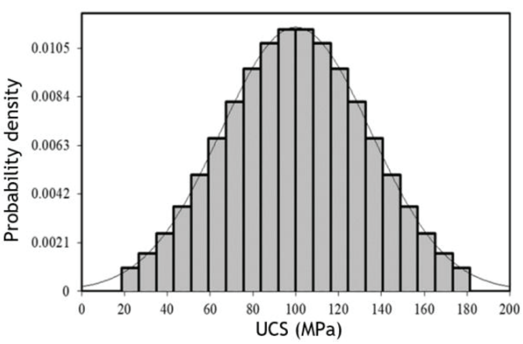

Figure 1. Probabilistic distribution function for UCS

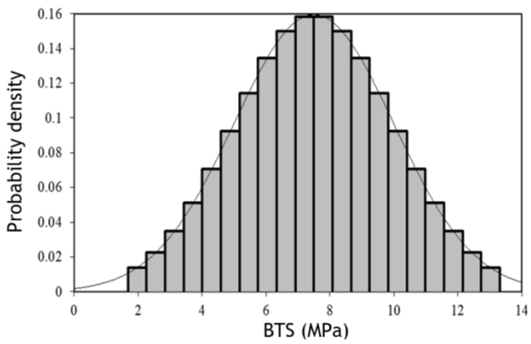

Figure 2. Probabilistic distribution function for BTS

The result of probabilistic analysis has been demonstrated through figure 3. As can be seen from figure 3, UCS has direct impact on measured rock brittleness, while an inverse effect of BTS on measures brittleness index is observed. The constants 0.807 and -0.485 were obtained on the basis of the probabilistic analysis results for the *a* and *b*, respectively. After substituting obtained coefficients, the final form of proposed brittleness index was achieved as follow (equation 7):

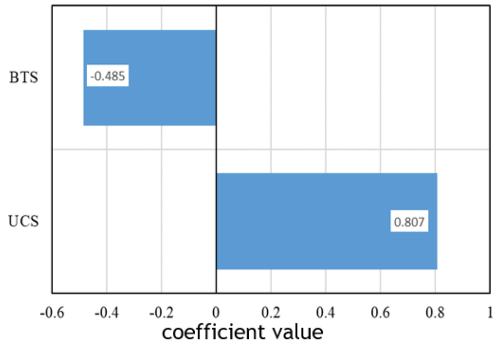

Figure 3. Impacts of input parameters of probabilistic analysis on measured rock brittleness

$$BI_n = \sigma_c^{0.807} \times \sigma_t^{-0.485} \tag{7}$$

MODEL VALIDATION AND DISCUSSION

In order to evaluate the performance of the index proposed, three indicators, including coefficient of determination (R2), root mean square error (RMSE), and variance account for (VAF) between measured and predicted value (MD) were used. A model is considered to be properly developed when R2 is 1, RMSE is 0 and VAF is 100. Equations 8 and 9 were applied in order calculate the RMSE and VAF.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - P_i)^2} \tag{8}$$

$$VAF(\%) = \left[1 - \frac{\mathrm{var}(M_i - P_i)}{\mathrm{var}(M_i)}\right] \times 100 \tag{9}$$

where M_i and P_i are correspondingly measured and predicted values of brittleness and *N* is the number of testing sample. The obtained values of each indicator for each index are listed in table 3.

Table 3. Performance prediction indicators values for each brittleness index

Brittleness index	Equation number	R2	RMSE	VAF (%)
BI_1	(1)	0.69	5.23	68.83
BI_2	(2)	0.63	5.62	64.35
BI_3	(3)	0.69	5.43	66.39
BI_4	(4)	0.69	5.43	66.39
BI_5	(7)	0.88	3.25	87.79

CONCLUSION

The main aim of this study was to develop a new brittleness index based on punch penetration test. For this purpose, by reviewing the existing strength-based brittleness, a general equation was suggested for the new index. In the next step, the coefficients of the proposed equation were calculated using an integrated approach based on the statistical analysis and probabilistic simulation. Consequently, the performance prediction of proposed index was compared with the existing brittleness indices. According to the obtained results, the values of 0.807 and 0.485 were proposed for UCS and BTS coefficients, respectively. For this aim, three indicators including coefficient of determination (R2), root mean square error (RMSE) and variance account for (VAF) between measured and predicted value (MD) were applied. When R2 is 1, VAF is 100% and MD is 0 the model would be an ideal one. It was found that, among different brittleness index, the index proposed in this study has the best R2, RMSE and VAF as 0.88, 3.25 and 87.79, respectively. Finally, it could be concluded that using the suggested index, rock brittleness can be predicted with high level of accuracy,

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