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Evaluating the strength of intact rocks through genetic programming

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ABSTRACT

Good prediction of the strength of rocks has many theoretical and practical applications. Analysis, design and construction of underground openings and tunnels, open pit mines and rock-based foundations are some examples of applications in which prediction of the strength of rocks is of great importance. The prediction might be done using mathematical expressions called failure criteria. In most cases, failure criteria of jointed rocks contain the value of strength of intact rock, i.e. the rock without joints and cracks. Therefore, the strength of intact rock can be used directly in applications and indirectly to predict the strength of jointed rock masses. On the other part, genetic programming method is one of the most powerful methods in machine learning field and could be utilized for non-linear regression problems. The derivation of an appropriate equation for evaluating the strength of intact rock is the common objective of many researchers in civil and mining engineering; therefore, mathematical expressions were derived in this paper to predict the strength of the rock using a genetic programming approach. The data of 51 rock types were used and the efficiency of equations obtained was illustrated graphically through figures.

1. Introduction

Rock materials (both intact and jointed) do not have uniform strength under different confining pressures and as the confining pressure σ_3 is increased, the strength of rock is subsequently increased. The correlation of these two parameters is different in different materials. In other words, $\sigma_1 = f(\sigma_3)$ and f may not be the same for different rock types.

Prediction of the strength under different confining pressures is important from numerous aspects. Quick and simple evaluation of the strength, instead of its direct measurement, is always desired and attracts engineers' attention especially in the phase of initial investigations and designs of rock projects and the structures related to rocks. On the other hand, in analysis and designs associated with rock slopes, underground excavations, mines, etc, equations are needed to determine the strength of rock continuously for different confining pressures. Such an equation is called "failure criterion". From one point of view, failure criteria related to rocks can be divided to two categories: "intact rock failure criteria" and "rock mass failure criteria" [1]. In present study, the emphasis is on the intact rocks.

The mechanical behavior of geotechnical materials, especially rocks, is more complicated rather than those of other materials. Therefore, analytic approaches have not been successful in this field. Griffith's method [2] is an example of analytic methods that solved the problem of determining the strength of rock assuming the existence of elliptic micro cracks in the rock. Predictions of Griffith failure criterion show considerable difference with the real values of strength, especially at high levels of confining pressure. This is due to simplifying assumptions used in the theory.

Several researchers have regarded another group of failure criteria called "empirical criteria" [1]. Empirical criteria are the equations that are obtained based on analyzing experimental data of strength of different rock types. For example, empirical criteria presented by Bieniawski [3] and Johnston [4] could be mentioned. In these criteria the relationship between strength and confining pressure is non-linear and the equation contains two constants. Bieniawski proposed the value of the constants for some rocks, i.e. sandstone, siltstone and mudstone. Johnston presented equations to obtain the value of the constants according to uniaxial compressive strength (UCS), i.e. the strength of rock when there is no applied confining pressure.

Empirical criterion of Hoek and Brown [5–7] is the most common failure criterion in studies of rock engineering. Applying some changes to their original criterion, Hoek and Brown proposed equations for predicting the strength of different kinds of rock, such as isotropic and anisotropic intact rock, heavily jointed rock and anisotropic jointed rock. Probably the most important shortcoming of this criterion for intact rock is the need to conduct several tests, at least five, in order to determine its constants [6]. There are

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also some guide-tables available. Marinos and Hoek [8], for example, presented such a table to determine constants of Hoek–Brown criterion for different rocks when laboratory equipments are not available. In order to determine the rock type precisely, sufficient experience and related knowledge is needed when these tables are used. Moreover, it is always probable that the real values of the constants have considerable difference with proposed average values [9].

Methods based on artificial intelligence such as artificial neural networks (ANN) and genetic programming (GP) can also be used to evaluate the strength of rock. Artificial neural networks that are used extensively in this field, actually, do an interpolation on a given set of data. Generally speaking, modeling and identification approaches taxonomy is two fold: firstly, white box models (which use differential equations for modeling) and secondly black box models with no differential equation. ANNs act like a black box. Although GP is also categorized in black box approaches, it gives mathematical expressions, which apparently show the relation between input and output. Therefore, GP is preferred in cases where researchers' desire is to have a well-form and simple mathematical expression in terms of their target mathematical operations and functions.

Despite of ANNs, GP has not been used extensively in rock mechanics and especially in predicting the strength of rocks. Recently in a study by GP, Baykasoğlu et al. [10] presented some equations for prediction of UCS and tensile strength of chalky and clayey limestone in terms of physical properties of the rock like density in different conditions and ultrasonic pulse velocity. However, it should be mentioned that direct measurement of UCS and tensile strength is a common and relatively cheap procedure in rock engineering.

In present study strength data of 51 different rock types taken from the literature [1] are utilized by GP and some equations are obtained to predict the strength of intact rocks. First, some equations are presented to determine the value of constants in Hoek–Brown criterion. Subsequently the strength of rock may be predicted using mentioned criterion and these equations. Then a criterion similar to Johnston's criterion is proposed and appropriate expressions are generated for one of its constants. Finally, GP is utilized to predict the strength of rocks without any basic equations. In all cases, the errors of the equations obtained indicate good efficiency of these equations. The proposed approaches are also compared and the best is determined.

2. Strength of rock

Conventional triaxial test, the most common approach to measure the compressive strength under different confining pressures, includes two main stages: (1) applying cell pressure, also known as confining pressure ($\sigma_{\rm con}$) and (2) inducing deviatoric pressure (σ_d) (Fig. 1). The value of compressive stress $\sigma_1 = \sigma_d + \sigma_{\rm con}$ at instant of failure is regarded as the strength of rock at the corresponding confining pressure $\sigma_3 = \sigma_{\rm con}$.

When no confining pressure is applied ($\sigma_3 = 0$), the strength of rock is referred to as uniaxial (or unconfined) compressive strength, UCS (σ_c). UCS is one of the most important characteristics of rocks and can be measured through various direct and indirect approaches [11]. One of the applications of UCS is in rock classifications. Various references proposed different classification systems for rocks according to the type of application [2,11]. For example, geomechanics classification and NGI method could be mentioned. In most cases for classification other factors like quality of joints (if exist) and ground water conditions should be considered in addition to UCS.

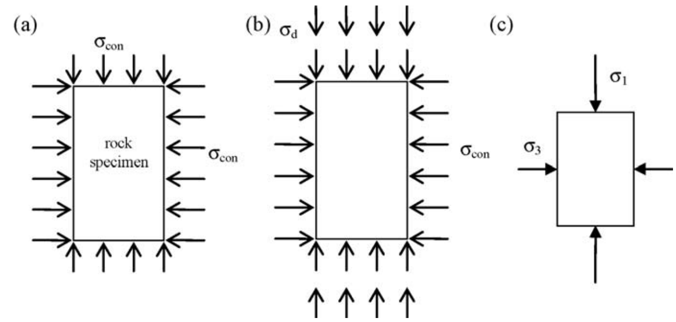

Fig. 1. Rock specimen under pressure in triaxial test. (a) Stage of applying confining pressure. (b) Stage of applying deviator pressure. (c) System of principal stresses.

Table 1
Triaxial test results on a natural sandstone [1].

σ_3 (MPa)	σ_1 (MPa)
−3.85	0
0	48.0
2.5	64.4
5	74.3
15	110
25	134.6
30	149.2
35	160.5

Protodiakonov [12] classified rocks into 10 main groups according to UCS and described each group with terms like strong, medium, weak, etc. Hoek and Brown have also used similar classification and descriptions [6,7].

Heavily jointed rock cannot withstand tensile stresses. However, intact rock may do it up to a limiting stress called tensile stress (σ_T). In fact, tensile strength is the value of tensile stress that a rock specimen can withstand in the absence of lateral confining pressure. Tensile strength is another important characteristic of rocks and could be indirectly measured through the relatively simple "Brazilian tension" test.

Triaxial test described formerly may be conducted on similar specimens under different confining pressures and thus a set of σ_3, σ_1 pairs will be obtained. Table 1 shows sample results for a type of natural sandstone.

Mohr–Coulomb criterion, the simplest failure criterion for rocks (geotechnical materials in general), assumes the relationship between major and minor principal stresses at the instant of failure to be linear. However, the relationship is rarely linear in practice. Mohr–Coulomb has also other shortcomings [11].

One of the non-linear forms proposed for above-mentioned relationship is Hoek–Brown failure criterion. This empirical criterion for intact rocks is given below [5]:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_i\frac{\sigma_3}{\sigma_{ci}} + 1\right)^{0.5} \tag{1}$$

where σ_{ci} is UCS and m_i is the Hoek–Brown constant for intact rock. Mohr–Coulomb and Hoek–Brown criteria are shown in Fig. 2 for strength data given in Table 1. As illustrated in this figure, Hoek–Brown criterion has appropriate degree of accuracy in predicting the non-linear strength behavior of the rock. However, it is not always possible to conduct several tests to determine constants of the criterion (m_i,σ_{ci}). Moreover, in order to use proposed constants, Marinos and Hoek for example, one should have enough knowledge and experience about rocks and the results are not precise all the times.