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Optimized Mamdani fuzzy models for predicting the strength of intact rocks and anisotropic rock masses

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ABSTRACT

Development of accurate and reliable models for predicting the strength of rocks and rock masses is one of the most common interests of geologists, civil and mining engineers and many others. Due to uncertainties in evaluation of effective parameters and also complicated nature of geological materials, it is difficult to estimate the strength precisely using theoretical approaches. On the other hand, intelligent approaches have attracted much attention as novel and effective tools of solving complicated problems in engineering practice over the past decades. In this paper, a new method is proposed for mining descriptive Mamdani fuzzy inference systems to predict the strength of intact rocks and anisotropic rock masses containing well-defined through-going joint. The proposed method initially employs a genetic algorithm (GA) to pick important rules from a preliminary rule base produced by grid partitioning and, subsequently, selected rules are given weights using the GA. Moreover, an information criterion is used during the first phase to optimize the models in terms of accuracy and complexity. The proposed hybrid method can be considered as a robust optimization task which produces promising results compared with previous approaches.

1. Introduction

One of the key problems in rock engineering is predicting the strength of rocks including intact rocks, anisotropic and highly fractured masses. Such a prediction has several practical applications, e.g. design and construction of rock-based structures, stability of rock slopes, and underground excavations. This problem may be dealt with via different techniques, including analytical, experimental and numerical methods. The analytical methods are generally either those introduced for solids in general (e.g. methods based on theory of elasticity) or those proposed particularly for rock materials.

Due to intrinsic complication of mechanical behavior of rocks, analytical solutions commonly fail to predict the value of strength accurately. The Griffith's method is one example of analytical methods that determines the strength of intact rock assuming the existence of elliptic microcracks in the rock (Jaeger et al., 2007). However, due to simplistic assumptions made in this theory, one may observe considerable difference between the real values of strength and those predicted by the Griffith failure criterion. Another analytical criterion proposed for anisotropic jointed rocks is that of Jaeger (1960). He assumed an anisotropic behavior when a jointed specimen tends to slide through its joint and calculated the strength by Mohr–Coulomb relation. This criterion also has shortcomings both in sliding and non-sliding modes of failure (Tien and Kuo, 2001). Consequently, most of researchers and practical engineers prefer to use the relations proposed based on analyzing experimental data (known as empirical failure criteria).

Recently, some techniques in artificial neural networks, fuzzy systems, and evolutionary computation have been attracting more and more attention in several research areas of rock mechanics (e.g. Alvarez Grima and Babuska, 1999; Sonmez et al., 2003; Garaga and Latha, 2010; Mishra and Basu, 2013). These methods usually have the advantages of the simplicity and applicability of experimental failure criteria as well as desirable accuracy of computational methods.

Combination of intelligent methods is a brilliant idea which results in powerful techniques having the advantages of different methods simultaneously. For example, in several recent researches, evolutionary algorithms (EAs) have been utilized in order to develop fuzzy systems (FSs) for modeling, identification and classification tasks (Eftekhari and Katebi, 2008; Asadi et al., 2013). These systems are generally called evolutionary fuzzy systems (EFSs). It will be noted that, developing a FS is a complex process and hence requires employing some optimization techniques to achieve more reliable results.

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The well-known Mamdani fuzzy inference system (MFIS) was first proposed to control a steam engine by a set of linguistic rules obtained from experienced human operators or experts. Since the MFIS uses fuzzy membership functions (MFs) for both input and output variables, it provides intuitive interpretation for human users. In current study, optimized MFISs are extracted utilizing binary genetic algorithm (GA) to provide a powerful tool for predicting the strength of intact rocks and anisotropic jointed rock masses. The proposed approach of modeling has two phases. First, some important rules are selected by the GA from a predefined rule base (RB) produced by means of grid partitioning. In this phase, both accuracy and compactness of the FS are considered and the FS would be optimized by defining a proper fitness function (the concept of information criteria). In the second phase, the GA is utilized once again but now for weighting the fuzzy rules selected from the previous phase. The proposed approach is finally evaluated through comparison of the models' outputs with experimental values of strength based on statistical criteria.

2. Rock strength

2.1. *Intact rock material*

Over the past decades, a large number of theoretical approaches have been proposed for evaluation of rocks and rock masses. The Mohr–Coulomb failure criterion is the simplest, but also the most widely used relation which assumes the relationship between shear and normal stresses on failure plane to be linear. The Mohr–Coulomb failure criterion in terms of principal stresses is of the following form:

$$\sigma_1 = \sigma_c + k\sigma_3 \tag{1}$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively; σ_c is the uniaxial (or unconfined) compressive strength (UCS); and k is the constant of the equation. The angle of internal friction (ϕ) and cohesion (c) may be then calculated by

$$\sin\phi = \frac{k-1}{k+1} \tag{2}$$

$$c = \frac{1-\sin\phi}{2\cos\phi}\sigma_c \tag{3}$$

Singh et al. (2011) made some modifications to the Mohr–Coulomb criterion to take nonlinearity of the strength into consideration. They introduced a new parameter called critical confining pressure into the original criterion. The value of critical confining pressure is evaluated through statistical analysis of experimental data by Singh et al. (2011) and proposed to be equal to the UCS.

Several investigators have analyzed experimentally the measured strength data of intact rocks and proposed empirical failure criteria. The Hoek–Brown criterion is the best-known empirical criterion which has been updated many times since its introduction in the early 1980s. The original form of this criterion for intact rocks is given below (Hoek and Brown, 1980):

$$\sigma_1 = \sigma_3 + \left(m\sigma_c\sigma_3 + \sigma_c^2\right)^{1/2} \tag{4}$$

where m and σ_c are constants of the criterion and may be determined either through curve fitting (over experimental data) or through practical guidelines provided by Hoek and Brown (1980).

Empirical relations commonly work well for those types of rocks that are similar to rocks used in derivation of the original equation. Furthermore, owing to some reasons such as rough surfaces of the rock, relative stiffness of testing apparatus compared with the specimen, inclination and eccentricity of the applied load, the strength values measured in the laboratory may exhibit substantial variances. In other words, the data used in such researches have an approximate nature. Consequently, it seems reasonable to have errors using exact relations obtained through such data.

2.2. *Anisotropic jointed rock mass*

Due to the presence of well-defined through-going joints, either in the form of single joint or a set of parallel joints, the mechanical properties of rock masses including their strength become directional or anisotropic. Failure of such rocks is examinable in two separate modes: sliding failure mode, and non-sliding failure mode. In the first case, rock failure occurs due to sliding on discontinuity (joint), while in the other case, it is impossible to slide on the joint and the failure of rock material occurs (Goodman, 2004).

Jaeger (1960) calculated the strength of rock with through-going joints under the conditions of sliding failure analytically and introduced the following equation:

$$\sigma_1 - \sigma_3 = \frac{2\left(c_j + \sigma_3\tan\phi_j\right)}{\left(1-\tan\phi_j\tan\beta\right)\sin(2\beta)} \tag{5}$$

where c_j and ϕ_j are the cohesion and friction angle of the joint surface, respectively; β is the angle between the joint and vertical axis as shown in Fig. 1a.

Sliding failure, however, occurs only in a limited range of discontinuity angles (β). Furthermore, as the confining pressure (σ_3) increases, the possibility of sliding decreases correspondingly. For very sharp or flat angles, Jaeger (1960) assumed the isotropic behavior for the jointed medium shown in Fig. 1a and attributed compressive strength of intact rock to it (Fig. 1b).

Tien and Kuo (2001) proposed a semi-empirical criterion for predicting the strength of jointed rocks with regard to the theory of elasticity. They accepted the sliding failure relation proposed by Jaeger (1960), but stressed that in non-sliding failure mode, rock samples have anisotropic behavior. This criterion requires at least seven laboratory tests to determine its input parameters.

Considering the shortcomings of analytical methods, some investigators have analyzed the experimental data and proposed some empirical relations to evaluate the strength of anisotropic rock masses. These empirical criteria have relatively higher accuracy and applicability compared with the analytical and theoretical

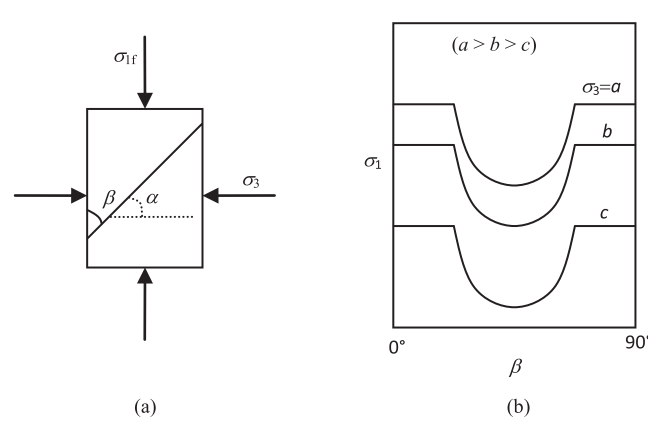

Fig. 1. (a) Anisotropic jointed specimen. (b) Typical Jaeger's criterion.