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Assessment of rock slope stability using the Fuzzy Slope Mass Rating (FSMR) system

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ABSTRACT

One of the useful methods for rock slope stability analysis is the Romana SMR classification. This method is a developed version of the Bieniawski's 'rock mass rating' (RMR) system. This classification is based on classic set theory. Characterization of rock's mass is very complex and may result in some ambiguous. The classic Sets Theory Classification is not able to yield to unambiguous results. Using fuzzy set theory is an effective approach to quantify these ambiguities. This paper describes the application of fuzzy set theory to SMR classification by incorporating fuzzy sets. In the proposed approach the Mamdani fuzzy algorithm was constructed using 825 "if–then" rules for evaluating rock slope stability. In addition, slope instabilities in an open pit mine were tested and results were evaluated to confirm the accuracy of implementation this proposed approach.

1. Introduction

Classification system can categorize objects or events by using common scales and terms. This system facilitates communication of information and guide detailed investigation. Furthermore, it can either predict their properties and behavior or establish relationships between them. This tool is a common method for designing of rock engineering. Rock mass classification evaluates performance of rock slopes based on the most important inherent and structural parameters.

In recent years, various empirical rock mass classification systems have been devised for the general assessment of slope stability. Table 1 shows the mentioned classification systems which can be utilized in slope stability design.

Amongst the referenced classifications, the SMR is a geo-mechanical classification which is mostly used in rock slope characterization. The SMR is obtained from the basic rock mass rating by using four factors that consider the geometrical relationship between the slope face and joint affecting rock mass as well as the excavation method.

Certain ambiguities are encountered subjectively in conventional rock classification systems as the result of:

(i) Using linguistic terms as input value of some parameters.
(ii) Applying same numerical scores in the regions of both lower and upper boundaries of class intervals.
(iii) Existence of sharp transitions between two adjacent classes, whereas the rock mass quality is gradational in nature.
(iv) Prescribed rating scales representing contribution of each criterion to the overall quality.
(v) Reliability of input value of each parameter.

Uncertainty is the lack of sufficient knowledge to make a decision. In rock slope problems, the results of analyses are greatly influenced by the uncertainties of mechanical characteristics. In contrast, fuzzy set theory enables to present a soft approach for quantifying these ambiguities by efficient participation of engineer's view. As the fuzzy models can cope with the complicated and ill-defined systems in a flexible and consistent manner, their applications in solving various problems in the field of mining geo-mechanics have been observed during the past two decades [32–48].

In this study, reference is made to SMR (one of the well-known conventional rock slope classification systems) to demonstrate the possibility of quantifying the ambiguities by using fuzzy set theory,

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Table 1
Existing rock slope classification systems.

Name of the system	Abbreviation	Authors	Comments
Rock mass rating	RMR	Bieniawski [1–4]	For application in slopes was added in the 1979 version of the RMR system.
Mining rock mass rating	MRMR	Laubscher [5–8]	Based on RMR (1973).
Rock mass strength	RMS	Selby [9,10], Moon and Selby [11]	Based on natural slope database.
Slope mass rating	SMR	Romana [12], Romana et al. [13]	Based on RMR (1979). The most commonly used classification system for slopes.
Slope rock mass rating	SRMR	Robertson [14]	Based on RMR. The classification is provided for of weak altered rock mass materials from drill-hole cores.
Chinese system for slope rock mass rating	CSMR	Chen [15]	Adjustment factors have been applied to the SMR system for the discontinuity condition and slope height.
Geological strength index	GSI	Hoek et al. [16]	Based on RMR (1976).
Modified mining rock mass rating	M-RMR	Unal [17]	For weak, stratified, anisotropic and clay bearing rock masses.
Geological strength index	GSI	Hoek et al. [18], Marinos and Hoek [19,20], Marinos et al. [21]	For non-structurally controlled failures.
Index of rock mass basic quality	BQ	Lin [22]	
Rockslope deterioration assessment	RDA	Nicholson and Hencher [23], Nicholson et al. [24], Nicholson [25–27]	For shallow, weathering-related breakdown of excavated rockslopes.
Slope stability probability classification	SSPC	Hack [28], Hack et al. [29]	Probabilistic assessment of independently different failure mechanics.
Volcanic rock face safety rating	VRFSR	Singh and Connolly [30]	For volcanic rock slopes to determine the excavation safety on construction sites.
Falling rock hazard index	FRHI	Singh [31]	Developed for stable excavations to determine the degree of danger to workers.

which provides smooth and gradual transitions between adjacent classes.

2. SMR classification

SMR was presented by Romana for geo-mechanical classification of slopes in rock. The SMR is calculated by adding four adjustment factors to the basic RMR. These factors depend on the relative orientation of joints, slope, and method of excavation. Hence, RMR is very useful as a tool for the preliminary assessment of slope stability.

2.1. Basic RMR

The basic RMR is computed based on Bieniawski's 1979 proposal [3]. It is obtained by adding five parameters that take into account uniaxial compressive strength or point load strength of the rock (R_{UCS}), spacing of discontinuities (R_{SD}), Condition of discontinuities (R_{CD}), Ground water inflow through discontinuities and/or pore pressure ratio (R_{GD}) and the Rock quality designation or RQD (R_{QD}):

$$\mathrm{RMR_b} = R_{UCS} + R_{SD} + R_{CD} + R_{GD} + R_{RQD} \quad (1)$$

RMR rating method is shown in Table 2, where, the five effective elements of RMR have been described. Discontinuity condition is a very complex parameter which includes several sub-parameters: roughness of discontinuity (RD), separation of discontinuity (SeD), persistence (PD), and weathering of discontinuity walls (WD). Romana presents list of partial parametric rating for joint condition (Table 3).

2.2. Adjusting factors

Adjusting factors are obtained from four different factors (Table 4). These factors are:

F_1: Depends on parallelism between discontinuity and slope face dip direction, where its range is from 0.15 to 1. These values match to the following equation:

$$F_1 = (1 - \sin A)^2 \quad (2)$$

where, "A" denotes the angle between the strikes of slope face and joints. Additionally, a factor "F_2" refers to discontinuity dip angle in the planar mode of failure, and its range is from 0.15 to 1.

$$F_2 = tg^2 B_j \quad (3)$$

where, B_j denotes the joint dip angle. For the toppling mode of failure, F_2 remains as 1.00. This parameter is related to the probability of discontinuity shear strength.

Other crucial values are described later in the paper that addresses such factors as:

F_3: Reflects the relationship between the slope face and discontinuity (values from 0 to −60).
F_4: Adjusting factor for excavation method has been fixed empirically (values from −8 to 15).

2.3. Total slope mass rating

The final slope mass rating is obtained using the following expression:

$$\mathrm{SMR} = \mathrm{RMR_b} + (F_1 \cdot F_2 \cdot F_3) + F_4 \quad (4)$$

These values are grouped into five slope stability classes, where the classes are broken in to sub-groups of twenty each. The empirical description of SMR classes is shown in Table 5. It gives a forecast of stability problems and support techniques for slopes per class.

3. Fuzzy sets theory

Fuzzy set theory is a generalization of classical set theory. It consists of mathematical tools which were developed to model and process incomplete information, ranging from interval-valued