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Rock slope stability analyses using extreme learning neural network and terminal steepest descent algorithm

A.J. Li [a,*], S. Khoo [a], A.V. Lyamin [b], Y. Wang [a]

[a] School of Engineering, Deakin University, VIC 3217, Australia
[b] Centre for Geotechnical and Materials Modelling, The University of Newcastle, NSW 2308, Australia

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ABSTRACT

The analysis of rock slope stability is a classical problem for geotechnical engineers. However, for practicing engineers, proper software is not usually user friendly, and additional resources capable of providing information useful for decision-making are required. This study developed a convenient tool that can provide a prompt assessment of rock slope stability. A nonlinear input–output mapping of the rock slope system was constructed using a neural network trained by an extreme learning algorithm. The training data was obtained by using finite element upper and lower bound limit analysis methods. The newly developed techniques in this study can either estimate the factor of safety for a rock slope or obtain the implicit parameters through back analyses. Back analysis parameter identification was performed using a terminal steepest descent algorithm based on the finite-time stability theory. This algorithm not only guarantees finite-time error convergence but also achieves exact zero convergence, unlike the conventional steepest descent algorithm in which the training error never reaches zero.

1. Introduction

It is often difficult to measure the strength of rock masses accurately because it is variable. Features of rock masses generally include joints, faults, and naturally occurring discontinuities and anisotropies. These features result in difficult analyses using simple theoretical solutions, such as the limit equilibrium method (LEM). Although many researchers have investigated the assessment of the stability of rock slopes [1–4], an accurate assessment continues to pose a major challenge to geotechnical engineers.

Although it has been known that the failure envelope of rock masses is nonlinear [5–7], the conventional linear Mohr–Coulomb criterion has been widely used. It would be due to the fact that most computer programs allow only the conventional Mohr–Coulomb strength parameters, cohesion and friction angle, to be used as inputs in slope stability analyses. In fact, the nonlinearity is more pronounced at low confining stresses, which exist in slope stability problems [8]. The studies of Li et al. [9,10] have shown that a linear failure criterion is not suitable for assessing rock slope stability. Therefore, the application of a nonlinear failure criterion, such as that proposed by Hoek [5], is necessary.

As discussed by Merifield et al. [11], the Hoek–Brown failure criterion is one of the few nonlinear criteria used by practicing engineers for estimating rock mass strength. In the current study, this failure criterion was adopted for determining the failure envelope of rock masses on slopes. Hoek et al. [12] expressed the latest version of the Hoek–Brown failure criterion as:

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b\frac{\sigma_3'}{\sigma_{ci}} + s\right)^{\alpha}, \tag{1}$$

where

$$m_b = m_i \exp\left(\frac{GSI-100}{28-14D}\right), \tag{2}$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right), \tag{3}$$

$$\alpha = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI}/_{15} - e^{-20}/_{3}\right). \tag{4}$$

The magnitudes of m_b, s, and α depend on the geological strength index (GSI), which indicates the rock mass quality and ranges between 5 and 100. GSI was introduced to estimate the rock mass strength for different geological conditions because Bieniawski's rock mass rating system [13] and the Q-system [14] had been found to be unsuitable for poor rock masses. As indicated by Hoek and Brown [15], GSI can be adjusted for incorporating the effects of surface weathering. The variables σ_{ci} and m_i represent the intact uniaxial compressive strength and material constant, respectively. The disturbance factor D, which ranges between 0 and 1, may result from the slope cutting process, for which there are several methods. Additional details on estimating the Hoek–

* Corresponding author at: School of Engineering, Deakin University, Pigdons Road, Geelong, VIC 3217, Australia. Tel.: +61 3 5227 2998; fax: +61 3 5227 6068.

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Brown strength parameters have been presented by Wyllie and Mah [16] and Marinos et al. [17].

Li et al. [18] showed that the evaluation of the factor of safety for rock slopes can differ considerably if the rock mass disturbance is considered, particularly for cases with a low *GSI*. In addition, Hoek et al. [12] indicated that the disturbance factor should be determined with caution. The importance of estimating *D* is therefore evident. For evaluations of *D*, some recommended magnitudes can be found in the study of Hoek et al. [12]; these magnitudes may serve as starting points for the initial assessment. These authors also stated that a more accurate estimate of the disturbance factor can be obtained by using field observations or measurements.

As highlighted by Burland [19], some of the geotechnical parameters used in the analysis may not be accurately measured in laboratory tests because of the effects of sample disturbance and errors of tests. Therefore, back analysis or the observational method, as suggested by Peck [20], is often applied to determine representative and/or dominant soil parameters based on actual field observations. To obtain more accurate assessments of the rock mass strength parameters, an artificial neural network (ANN) [21–23] is applied to back calculate failed rock slopes on the basis of the Hoek–Brown failure criterion.

2. Previous studies

2.1. Limit equilibrium analysis

In general, LEMs such as those proposed by Bishop [24] and Janbu [25] are the most widely used methods for estimating slope stability. Because of their simplicity, these methods are also used to obtain the uncertain parameters during slope failure [26,27]. In addition, the stability charts proposed by Hoek and Bray [1] can be used by practicing engineers to back analyze rock slopes. These chart solutions contain information on the water table and are suitable for the analysis of uniform rock and rockfill slopes. However, the conventional Mohr–Coulomb parameters (c' and ϕ') of rock masses are still required as inputs for estimating slope stability.

Sonmez et al. [28,29] back analyzed slope failures to obtain rock slope strength parameters. They explained the applicability of rock mass classification, and a practical method for estimating the mobilized shear strength based on the Hoek–Brown failure criterion. They concluded that shear strength determination is very difficult for jointed rock masses, possibly because of the scale effect. Unlike the latest version of the Hoek–Brown failure criterion [12], the rock mass disturbance was considered by using a different parameter in the study of Sonmez et al. [28]. Such consideration was not straightforward in the current study.

Comparisons between Bishop's simplified method [24] and the finite element upper and lower bound limit analysis methods for rock slopes were performed by Li et al. [9] by using the strength parameters of the Hoek–Brown failure criterion [12]. In their study, the factor of safety was found to be overestimated (>10%) when compared with the upper bound solutions. As stated by Li et al. [10], the best solution is not guaranteed if the slip surface should be assumed prior to any factor of safety calculation.

2.2. Numerical analysis

As mentioned previously, rock masses are heterogeneous, discontinuous media composed of rock materials and naturally occurring discontinuities such as joints, fractures, and bedding planes. The displacement finite element method and finite difference method are not suitable for analyzing rock masses with fractures and discontinuities. Stead and Eberhardt [30] observed that rock slope analyses, especially for displacement simulations, are highly sensitive for rock slope analyses. Recently, stochastic and statistical approaches have been used for evaluating rock mass characteristics and rock slope stability [31–34]. In reliability analyses, the influence of each uncertain parameter can be identified by considering various uncertainties.

A literature review reveals that the majority of back analysis studies based on numerical analyses have focused on the stress states and/or displacement during rock slope failures [30,35–38]. Although the Mohr–Coulomb model was used in some of these studies, the magnitude of the factor of safety was not discussed, probably because in numerical analyses, slope failure must be determined subjectively by considering plastic zones or displacements [39,40]. In the study of Deng and Lee [38], an ANN was trained and used as a benchmarking tool to obtain a more reliable prediction of slope displacement. Thus, the advantage of using an ANN is evident.

2.3. Back analysis techniques

Recently, optimization techniques, such as ANNs and genetic algorithms (GAs), have been applied to many geotechnical investigations, including the evaluation of soil and rock properties [41,42], anchor and bearing capacity [43,44], ground movements [45,46], and slope failure probability [47]. The techniques are mainly used to estimate factors that are difficult to measure directly or accurately; moreover, compared with the conventional trial-and-error method, they involve a considerably shorter computation time [31].

Although Sonmez et al. [28,29] have used the Hoek–Brown failure criterion for back analyzing slope failures, they considered the rock mass disturbance by using a different factor. To date, there has been no investigation (using an ANN) based on the latest version of the Hoek–Brown failure criterion [12], which can be useful in determining uncertain parameters during slope failure. Moreover, a literature review reveals that rock slopes have not been back analyzed on the basis of numerical limit analysis solutions. In the current study, an ANN was employed to train a package that can either assess slope stability or perform back analysis at a time. This package can also estimate single and/or multiple uncertain parameters for use in back calculations.

3. Methodology

3.1. Finite element upper and lower bound limit analysis methods

To train the back analysis tool, the finite element upper and lower bound limit analysis (LA) methods developed by Lyamin and Sloan [48,49] and Krabbenhoft et al. [50] were employed. These techniques can be used to bracket the true stability solutions for geotechnical problems [51–54] and are suitable for both linear and nonlinear failure criteria. Based on the Hoek–Brown failure criterion [12], these techniques have been used to assess rock slope stability and their applicability has been verified [18]. Numerical LA methods are ideal tools for generating training data for an ANN.

By using the limit analysis techniques developed by Lyamin and Sloan [48,49] and Krabbenhoft et al. [50], a statically admissible stress field for the lower bound analysis and a kinematically admissible velocity/plastic field for the upper bound analysis were contained. Furthermore, certain arbitrary assumptions made in the LEM can be avoided, such as those related to the inter-slice forces and slip surfaces.

In the numerical limit analyses, for a given slope height (H), slope angle (β), and rock mass strength (σ_{ci}, GSI, m_i, D), the optimized solutions of the upper bound and lower bound (LB) programs can be obtained with respect to the unit weight (γ) of the rock mass. Based on the Hoek–Brown failure criterion [12], Li et al. [55] proposed a non-dimensional stability number (N_r), which is given by

$$N_r = \frac{\sigma_{ci}}{\gamma \mathrm{HF}}, \tag{5}$$

where *F* is the factor of safety of the rock slope. As stated by Li et al. [18], the factor of safety can be presented in terms of $\sigma_{ci}/\gamma H$ because these