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Indirect measure of shale shear strength parameters by means of rock index tests through an optimized artificial neural network

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ABSTRACT

Shear strength is one of the most important features in engineering design of geotechnical structures such as embankments, earth dams, tunnels and foundations. Shear strength parameters describe how rock material resists deformation induced by shear stress. Rock shear strength parameters are usually measured through laboratory tests, and these methods are destructive, time consuming and expensive. In addition, providing good-quality core samples is difficult especially in highly fractured and weathered rocks. This paper presents an indirect measure of shear strength parameters of shale by means of rock index tests. In this regard, 230 shale samples were collected from an excavation site in Malaysia and shear strength parameters of samples were obtained using triaxial compression test. Furthermore, rock index tests including dry density, point load index, Brazilian tensile strength, ultrasonic velocity, and Schmidt hammer test were conducted for each sample. A particle swarm optimization-artificial neural network (PSO-ANN) integrated model was developed by setting the results of rock index tests as inputs and shear strength parameters as outputs of the model. The obtained correlation of determination of 0.966 and 0.944 for training and testing datasets show the applicability of the proposed model to predict shale shear strength parameters with high accuracy.

1. Introduction

Reliable estimation of rock strength and deformation parameters is always required for geotechnical engineering applications such as slope design and underground excavation. Rock shear strength parameters are widely used to design rock engineering structures. Shear strength parameters describe how rock material resists deformation induced by shear stress. This resistance is generally attributed to two internal mechanisms; interlocking (c) and internal friction angle (ϕ). However, there are some hindering parameters for direct determination of rock shear parameters in laboratory. Providing good quality core samples is difficult especially in highly fractured, weak and weathered rocks. Apart from that, direct method for determination of these parameters is destructive, time consuming and expensive [1]. Hence, indirect estimation of rock shear strength parameters using some rock index tests is of interest, as they are economical and easy to conduct.

In terms of rock shear strength studies, a large number of researches have been conducted by many scholars [2–8].

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Several researches have been performed on the shear strength of clay and sand with variable rock particle mixtures. In general, these studies indicate that the shear strength of the mixture increases with the increasing percentages of rock particles [9]. Singh and Singh [10] established a modified non-linear Mohr–Coulomb strength criterion for jointed rocks. They propounded two limitations of Mohr–Coulomb strength criterion; the linear strength response and ignoring the effect of the intermediate principal stress on the strength behaviour. They employed Barton's critical state concept [11] to obtain the non-linear strength criterion. Back analysis of more than 730 triaxial test results suggested the applicability of the proposed model. Various types of mudrock including 45 samples were used by Hajdarwish and Shakoor [12] to establish a correlation between shear strength parameters and geological and engineering properties using bivariate and multiple regression techniques. For this purpose, clay content, clay mineralogy, water content, Atterberg limits, specific gravity, dry density, void ratio, absorption, adsorption, slake durability, and shear strength parameters for each sample were determined. Results show that the selected parameters can be used for prediction of interlocking and friction angle of mudrock.

A comparative study was conducted by Yazdani [13] on shear strength parameters of shale using Mohr–Coulomb and new Hoek–Brown [14] failure criteria. The results obtained by this study indicate that the failure envelope obtained using the new Hoek–Brown criterion shows a better representation of shale under field condition. He also noted that shear behaviour based on classical Mohr–Coulomb criterion represents the behaviour of intact rock, without considering the presence of discontinuities in rock mass. Ghazvinian et al. [15] indicated that the angle of inclination of schistosity planes (β) within texture of intact rock sample exhibits anisotropic shear behaviour against external loading, in respect of normal stress orientation. In addition, they demonstrated that the effective shear strength values in terms of angle of β ranged from a maximum to minimum magnitude depending on concurrent effects of confinement stress and anisotropy. Islam and Skalle [16] evaluated shale mechanical properties based on accounting for the beddings plane, variable confinement pressures and drained/undrained test mechanisms. Results of experimental tests indicate that shale has a significant level of heterogeneity and that the drained Poisson's ratios are lower than the undrained rates by about 40%. Barton [17] investigated the shear strength criteria for rock joints, rockfill and rock masses and stated that the classical Mohr–Columb model needs to be nonlinear to better demonstrate the behaviour of intact rock strength.

The capability of artificial intelligence techniques in the field of geotechnical engineering [18–24] and more specific, in rock mechanic [25–35] has been highlighted in literatures. Artificial neural networks (ANNs), as powerful tools of artificial intelligence, is one of the most dynamic areas of research in advanced and diverse applications of science and engineering. Although ANNs are able to apply all influential factors in prediction models, they still have some limitations including the slow rate of learning and entrapment in local minima [36–38]. To overcome these restrictions, the use of powerful optimization algorithms is advantageous. Particle swarm optimization (PSO) is a powerful population-based technique for solving continuous and discrete optimization problems. Since PSO is a robust global search algorithm, it can be utilized to determine weights and biases of ANN in order to improve its performance. This paper presents a hybrid PSO-ANN integrated model to predict shear strength parameters of shale using some index tests (*i.e*. dry density (DD), point load index (Is(50)), Brazilian tensile strength (BTS), ultrasonic velocity (Vp), and Schmidt hammer rebound number (SHn)). For the sake of comparison, regression analysis was performed for both interlocking and friction angle of shale samples.

2. Behaviour of shale rock under triaxial test

Shear strength parameters are the most important mechanical properties of rock material which describe the behaviour of intact rock under shear failure. Shear strength is used to describe rock material strength against deformation induced by shear stress. This strength is generally recognized by two internal mechanisms including interlocking and internal friction angle. Interlocking is an internal bonding of rock material which depends on the surface texture along with the roughness of rock mass joint. The contact between rock particles creates internal friction is measured through the angle of internal friction. Fundamentally, triaxial compression test can be utilized to determine shear strength parameters.

Rocks with uniaxial compressive strength (UCS) in the range of 0.5–25 MPa are considered as soft or weak rocks [39]. The long process of compaction and cementation of clay minerals builds up a type of rock known as sedimentary rock (such as shale). The textures of these rocks contain very distinctive lamination and specific arrangement of minerals due to sedimentation. Therefore, failure can occur easily along these small-scaled lamination planes. Under this condition, the state of failure is commonly defined as shear failure.

Due to various fabrics or microstructure orientations together with bedding planes, the behaviour of shale is anisotropic. There are different anisotropy states with varying degrees of complexity [40]. In the case of rock material with anisotropic behaviour subjected to triaxial compression condition, principal stress difference ($\sigma_1 - \sigma_3$) can be derived from the following equation [41]:

$$(\sigma_1 - \sigma_3) = (2C_w + \sigma_3 \tan \varnothing_w)/(1 - \tan \varnothing_w \cot \beta) \times \sin 2\beta \quad (1)$$

where c_w is interlocking of fracture planes, $\varnothing_w$ is the friction angle of the plane and β depicts inclination angle of weakness plane. When the inclination angle is equal to $45 + 0.5\varnothing_w$, the value of strength is at minimum. Therefore, related value of principle stress difference is changed as follows:

$$(\sigma_1 - \sigma_3)_{min} = 2(C_w + \sigma_3 \tan \varnothing_w)[(1 + \tan^2 \varnothing_w)^{1/2} + \tan \varnothing_w] \quad (2)$$