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A polyaxial strength model for intact sandstone based on Artificial Neural Network

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ABSTRACT

A comprehensive database of the polyaxial compressive strength of eight sandstones has been compiled from the literature. An experimental study has also been conducted on local sandstone to add up to the database. A correlation-based analysis has been performed to find out the influence of each independent parameter namely uniaxial compressive strength (*UCS*, σ_{ci}), minor principal stress (σ_3), and intermediate principal stress (σ_2) on the strength of sandstone, i.e., the major principal stress at failure (σ_1). Additionally, a feed-forward back-propagating neural network (FFBPNN) has been proposed as a new polyaxial strength model to predict the strength of intact sandstone under polyaxial states of stresses. The database on polyaxial strength of 192 experiments on nine different sandstones has been randomly divided into a training set and a testing set. Three input parameters corresponding to the independent parameters (σ_{ci}, σ_3, σ_2) and one output parameter corresponding to the dependent parameter (σ_1) are considered. The accuracy of the proposed ANN based polyaxial strength model has been compared with five other conventional polyaxial criteria: modified Wiebols and Cook criterion (MWC), Mogi-Coulomb criterion (MC), modified Lade criterion (ML), 3D version of Hoek-Brown criterion (3DHB) and modified Mohr–Coulomb criterion (MMC). It is found that the ANN based failure model gives the best result amongst all the considered polyaxial strength criteria, for the testing dataset.

1. Introduction

The design and analysis of deep underground facilities in rockmass require the strength characteristics of the rock and rockmass around. The state of stress surrounding the rock structures, in general, is considered to be in conventional triaxial condition ($\sigma_2 = \sigma_3$). However, various researchers opined that the in-situ state of stress in rock is seldom triaxial but polyaxial i.e. ($\sigma_2 > \sigma_3$). This condition is more common in deep underground structures as well as in the area of high tectonic activity.[1,2] The strength of rock must, therefore, be estimated under the polyaxial state of stress for a better design. The testing under polyaxial state of stress is therefore must so as to have a realistic estimation of the strength of rock. The effect of intermediate principal stress on the strength of rock has been investigated in the past. Murrell [3] analysed the result of conventional triaxial compression test ($\sigma_1 > \sigma_2 = \sigma_3$) [4] and conventional triaxial extension test ($\sigma_1 = \sigma_2 > \sigma_3$) [5] conducted on white Carrara marble and concluded that the strength of rock is dependent on the intermediate principal stress. The findings were reaffirmed by the experimental investigation of Murrell,[6] Handin et al. [7] and Mogi.[8] This has led to the beginning of the polyaxial testing on the rock where all the three principal stresses are applied independently. Polyaxial tests were conducted by various researchers on indigenously designed machines for applying the three principal stresses. The researchers estimated a substantial effect of intermediate principal stress on the strength of the rock (major principal stress at failure). Details of various polyaxial tests conducted worldwide and the results are available in the literature.[9–31]

The polyaxial strength criteria were also presented by various researchers to predict the strength of rock under varying polyaxial conditions. Drucker and Prager (DP) criteria,[32] Mogi or Power-Law criterion,[9,10] modified Weibols and Cook (MWC) criterion,[33] modified Lade (ML) criterion,[34] Unified strength criterion,[35] Mogi Coulomb (MC) criterion or Linear failure criterion,[36] Extended Mogi Coulomb criterion,[37] 3D version of Hoek and Brown (3DHB) criterion,[38] You criterion,[39] modified Mohr Coulomb criterion [40] and Rafiai Criterion [41] are some of the criteria which are in vogue for predicting polyaxial strength of rock. Few comparative assessments of these criteria on the basis of various goodness of fit on published test data has also been presented by some researchers.[40,42,43] Kwaśniewski [44] collected a database of twenty-nine different polyaxial tests and presented quantitatively the comparison of three strength criteria.[9,10,36,38]

Artificial Neural network (ANN) is a statistical modelling technique

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which works on the principle of mimicking capability of the human brain. ANN is supplied with a set of observed input and corresponding observed target set of data. ANN modifies its internal structure to predict output very close to target data provided. Researchers have attributed the use of observed data for training, as the main reason for superior predictive power of ANN compared to conventional models. Recently, this soft computing technique has been used in various geotechnical engineering applications. ANN in general is used for a number of cases where predicting capability is needed and has demonstrated high degree of success. In the field of rock mechanics, ANN is also gaining acknowledgement for the development of various strength and deformation criteria. The uniaxial compressive strength and tensile strength of different intact rocks have been predicted using ANN by some researchers.[45–49] Sonmez et al. [50] and Ocak and Seker [51] used ANN for the determination of the deformation modulus of intact rock specimens. Maji and Sitharam [52] used ANN based model for the prediction of elastic modulus of jointed rock mass. Rafiai and Jafari [53] and Rafiai et al. [54] explored the possibility of developing new rock failure criteria using ANN for triaxial and polyaxial condition. Rafiai and Jafari [53] developed ANN based triaxial strength criteria for eight different rock types and compared the predicted value of major principal stress with that of experimental investigations against two most commonly used triaxial criteria. The ANN based criteria showed significant improvement in the prediction of major principal stress. Rafiai et al. [54] developed the ANN based polyaxial strength criterion for six different rock types and showed that the prediction from ANN based criteria were better than two conventional criteria namely modified Weibols and Cook criterion and Rafiai criterion. Kounda [55] studied the effect of intermediate principal stress on the strength of intact rock by five different ANN based criteria developed for five different rock types.

The ANN based criteria developed by Rafiai et al. [54] and Kounda [55] considered only one dataset for each rock type. The input parameters considered are only minor and intermediate principal stress. The effect of uniaxial compressive strength has not been considered which also affects the polyaxial strength of rock. The goodness of fit of the presented criteria for a new dataset for the same rock type will be different. Thus the ANN based criteria presented by the researchers fits only for the data set considered and not on general rock of a given type. Although this ANN based criterion proved to have a better performance however it needs a revision where it should include more input parameters in order to be used as general criterion for a given rock type.

In this paper, a new ANN based polyaxial strength model has been presented to predict the polyaxial strength of intact sandstone. A database of eight experimental investigation conducted worldwide had been collected from literature. In addition, an experimental investigation has also been conducted by the authors of the paper to assess the effect of intermediate principal stress on the strength of intact sandstone. The results of the experimental study conducted have also been added to the database. The total database thus consists of 192 experimental results of nine different sandstones. A correlation based analysis has been conducted on polyaxial strength database to determine the influence of each independent input parameter on the strength of sandstone. A connection weight analysis has also been conducted to quantitatively assess the contribution of each independent input parameter in the network. A quantitative comparison of the goodness of fit of the proposed ANN based strength model with five other commonly used conventional polyaxial strength criteria namely, 3D version of Hoek-Brown criteria (3DHB), modified Weibols and Cook criterion (MWC), Mogi-Coulomb criterion (MC), modified Lade criterion (ML) and Modified Mohr–Coulomb criteria (MMC) has been also made.

2. Experimental program

An experimental investigation program has been undertaken to study the strength behaviour of sandstone under polyaxial state of stress. The methodology involved has been discussed hereunder.

2.1. Rock samples

The present study has been conducted on natural sandstone obtained from Shivpuri district located in northern part of the state of Madhya Pradesh, India. The Shivpuri sandstone is characterized by their brownish pink color. The sandstone belongs to the Vindhyan formation. Petrographic study has been conducted on the rock samples. The thin section has been studied under optical microscope at 200 µm resolution. It has been found that the rock has almost 80–85% quartz and 15–20% of feldspar, without any micaceous mineral and is undeformed.

The quarrying of sandstone was done manually such that almost cubical samples of size 150 mm×150 mm ×150 mm were obtained. Cubical specimens of size 100 mm×100 mm ×100 mm have been prepared by cutting the specimen on high power hexa cutting machine. The cutting has been done very carefully so that the orthogonality of specimen faces was maintained. The specimens were then carefully grounded and lapped with the help of manual polishing machine. A total of thirty specimens were prepared.

The Shivpuri Sandstone has the unit weight of 23.99 kN/m^3, average uniaxial compressive strength (σ_{ci}) of 34.62 MPa, average tangent modulus of 7.23 GPa, The average shear strength parameters obtained for confining pressure range of 0–10 MPa, have been found to be cohesion (c_i) as 6.44 MPa and angle of internal friction (φ) as 48.93°. The rock has been classified as 'DL' as per the Deere-Miller Classification system.[56]

2.2. Testing apparatus

Many polyaxial testing systems have been developed by a number of researchers with the aim of applying the intermediate principal stress independently. Takahashi et al. [14,57] and Mogi [10] have grouped the polyaxial testing equipment in three broad categories namely, rigid platen types, flexible medium type and mixed or Mogi Type.

Li et al. [58] presented comparative assessment of these systems and discussed their relative merits and demerits. They opined that none of the three systems is near to perfect. However, the Mogi type apparatus has a number of advantages like low end-friction. Kwaśniewski [40] collected a database of polyaxial testing conducted on intact rock worldwide. He also mentioned the type of testing system employed for each test. Although many tests have been conducted with Mogi type apparatuses, few studies have also been conducted with rigid platen types [23,27–31,59–61] and flexible medium type [12,13,16,18] apparatus.

For the present study, the polyaxial testing system developed by Wille-Geotechnik Germany has been used. The testing system conforms to rigid platen type and has the same working principle as given by King et al.[59] The testing system has four basic units namely specimen holder, the power-pack, the pressure intensifiers and controlling workstation. The specimen holder has a three pair of piston system arrangement from all the six direction with the help of which uniform pressure can be applied on the rock specimen. The pressure is applied with the help of pressure plate having dimensions of 94 mm×94 mm. Fig. 1 shows the specimen holder, the pressure plate and the piston system. The power-pack generates the initial pressure which gets intensified in the intensifiers. The intensifier maintains the pressure in the specimen holder piston system. The machine can generate a maximum pressure of 140 MPa. The LVDT associated with the pressure plates measures the deformation in all the six directions. The deformation measured was used to calculate the strain in the specimen. The complete system is fully automated. The testing is controlled and coordinated by GEOsys software from the workstation.

2.3. Test program

The polyaxial tests were conducted on twenty-five specimens, while fives pecimens were used for uniaxial compression test. The polyaxial