Modelling the shear behavior of clean rock joints using Adaptive Neuro-Fuzzy Inference Systems

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ABSTRACT: Currently, the development of accurate and reliable models for predicting the behavior of rock mass joints is one of the most common interests among researchers, engineers and geologists. An alternative to address this type of problem more efficiently can be neuro-fuzzy systems, which combine the advantages of Fuzzy Controllers and Artificial Neural Networks (ANN). Therefore, the objective of this paper is to use Adaptive Neuro-Fuzzy Inference Systems (ANFIS) to predict the shear strength and corresponding dilation of unfilled discontinuities of rock masses, incorporating the uncertainties of the variables that govern their shear behavior. It was found that the proposed ANFIS models can be considered a useful tool to predict the shear behavior of clean discontinuities, as they require only some information about the joints characteristics, the intact rock that constitutes their walls, and the boundary conditions imposed on them, without the need for costly and complex laboratory tests.

Keywords: Clean rock joints, Shear behavior, Neuro-fuzzy, ANFIS, Modelling.

1 INTRODUCTION

The development of accurate and reliable models for predicting the behavior of rock mass discontinuities is one of the most common interests among researchers, engineers and geologists. However, Grima (2000) points out that exact solutions to problems in engineering geology rarely exist, since the relationships between the different variables that describe a given geological phenomenon are not known precisely, besides the intrinsic presence of uncertainty and imprecision in their values.

An alternative to address problems of this type more efficiently may be the neuro-fuzzy systems, which combine the advantages of Fuzzy Controllers and Artificial Neural Networks (ANN). While the first one attempts to reproduce the psychology of the human brain by means of the Fuzzy Logic (Zadeh 1965), the second simulates its physiology. According to Singh et al. (2012), this combination provides an interesting tool to describe complex, nonlinear and multivariate problems, such as those observed in geotechnical works designed and built-in rock masses. Regarding rock joints, Matos et al. (2018), Matos et al. (2019) and Dantas Neto et al. (2019) reported that the use of neuro-fuzzy systems can be a pertinent resource to model their shear behavior.

Therefore, the main objective of this paper is to present the results of the prediction of the shear behavior in unfilled rock mass discontinuities as a function of the main variables that govern the phenomenon, such as the normal stiffness and the initial normal stress of the joint, its roughness represented by the JRC value, the properties of the intact rock, portrayed by the simple compressive strength and the basic friction angle, and the shear displacement imposed on the discontinuity. The models developed consisted of two Adaptive Neuro-Fuzzy Inference Systems (Jang 1993) used to determine the shear strength and the corresponding dilation of the discontinuity. For the construction of these models, 44 direct shear tests on different types of joints and under different boundary conditions were selected. The results of the prediction of the shear behavior of unfilled discontinuities by the proposed neuro-fuzzy models fitted very well to the experimental data used in their development besides considering how they responded to the variability or uncertainty of each input variable of the studied phenomenon. In addition, it was proven the great potential of neuro-fuzzy systems for the solution of complex phenomena since combined with a large data set and quality.

2 ANFIS MODEL DEVELOPMENT

Knowing that the success of a neuro-fuzzy system depends on a large, comprehensive and reliable set of input and output data in order to establish that the rules governing its operation closely represent the reality of the physical phenomenon studied, the proposed models were developed based on a dataset with 44 direct shear tests performed by Benmokrane & Ballivy (1989), Skinas et al. (1990), Papaliangas et al. (1993), Indraratna & Haque (2000) and Indraratna et al. (2010) at different types of discontinuities (saw-tooth, tension-model, field-model and field-natural) and under different boundary conditions. Thus, a total of 673 shear force displacement examples from the experimental data set were used, considering the main factors governing the shear behavior of unfilled discontinuities as input variables, i.e., the normal boundary stiffness (k_n), initial normal stress (σ_{n0}) acting on the discontinuity, joint roughness coefficient (JRC), uniaxial compressive strength of the intact rock (σ_c), the basic friction angle (φ_b), and shear displacement (δ_h) having as its response the shear strength (τ_h) and the respective dilation (δ_v) of the discontinuity.

The definition of the proposed models was performed in MATLAB and went through a preliminary phase that contemplated the implementation of different types of neuro-fuzzy models following the methodology presented by Jang (1993). For the construction of each ANFIS model, the training phase was performed considering 80% of the input and output examples randomly selected from the learning database, while the remaining 20% were used in the validation phase. It is important to emphasize that the validation phase, responsible for evaluating the generalization ability of the neuro-fuzzy model, was done with data checking, that is, the neuro-fuzzy system was selected to have parameters associated with the minimum error relative to the validation data set. The hybrid learning rule was used to correct the premise or antecedent parameters, which define the membership functions, and the consequent parameters, which are related to the determination of the output variables. It was decided to use 50 epochs in the training phase and zero tolerance for the errors.

In this paper, the operation of the ANFIS model is analogous to the fuzzy controller proposed by Takagi & Sugeno (1983). Some alternatives were chosen to obtain the model with the best accuracy in relation to the validation data set. Each model consisted of two Multiple Input Single Output (MISO) systems whose the output variable was τ_h or δ_v. The basic differences between each model analyzed were in the way of obtaining the fuzzy inference system and in the input variables adopted.

It is worth noting that, during the application in MATLAB, the parameters entered in the subtractive clustering technique, such as range of influence and accept ratio, were kept in the default mode. In the models that used only four variables, the inputs were chosen based on the results of Dantas Neto et al. (2017) that presented the parameters that most interfere in τ_h e δ_v. For shear strength, the parameters k_n, σ_c, σ_{n0} e δ_h were adopted. Regarding the dilation, JRC, σ_c, k_n e δ_h were used.

Jang & Sun (1995) do not recommend the use of the grid partitioning technique for systems that have many input variables, since the size of the rule set varies exponentially with the number of pertinence functions and input variables. The authors do not set a limit on the number of inputs that could make the use of this technique unfeasible, but they clarify that the larger the number of input variables, the smaller must be the number of their membership functions for the grid partitioning technique to remain viable. In view of this, it was established in this work that the models that employed the grid partitioning technique were conditioned to use, at most, a total of 100 inference rules. This fact can be justified by the feasibility of the computational time required to obtain the optimized fuzzy inference system. All models obtained maximum optimization of their parameters in the second epoch. Finally, the model that presented the smallest mean absolute errors of τ_h and δ_v from the validation data was selected. The average errors of each model are summarized in Table 1.

Table 1. Mean absolute errors from validation data.

Fuzzy inference system	Generating method	Inputs	Mean absolute error	
			τ_h (MPa)	δ_v (mm)
Takagi and Sugeno (1983)	Grid partitioning	6	0.09	0.07
	Subtractive clustering	6	0.17	0.19
	Grid partitioning	4	0.20	0.30
	Subtractive clustering	4	0.31	0.39

Therefore, the model with 6 input variables using the grid partitioning technique with two Gaussian membership functions for each input was the one that presented the best fit. The selected model presented 64 fuzzy inference rules for determining τ_h and δ_v. An example of the membership function of one of the input variables with all its properties already defined is presented in Figure 1 for JRC.

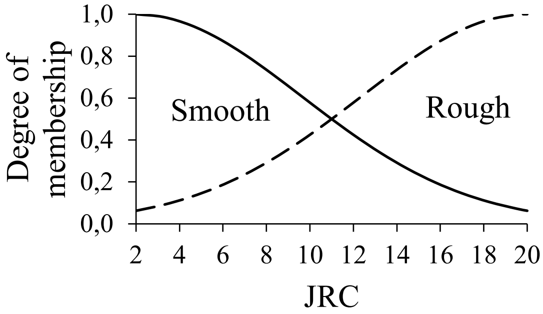
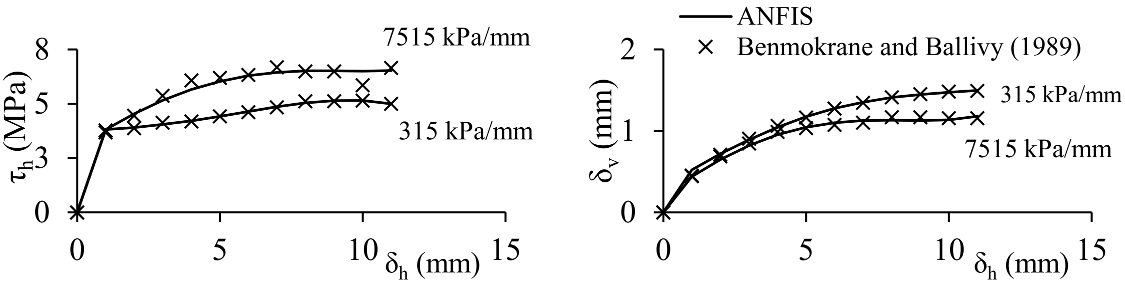


Figure 1. Membership functions for the JRC.

3 RESULTS AND DISCUSSION

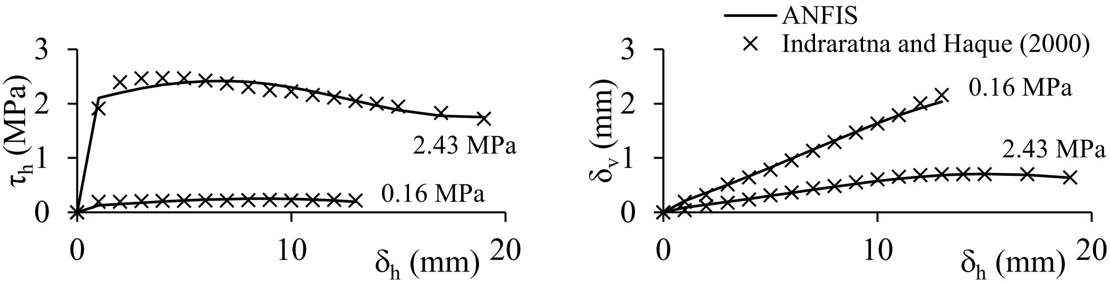
Figures 2 and 3 show comparisons between the experimental data and the values predicted by ANFIS to evaluate whether the models can portray the influence of the governing parameters on the shear behavior of an unfilled discontinuity. For the scenarios analyzed, it was found that the ANFIS was able to consider the effects of the boundary conditions imposed on the shear behavior of the discontinuities. Furthermore, its predictions conformed to the experimental data with good approximation. Thus, resorting to a more detailed verification of the performance of the proposed model, Figure 4 presents its deviations from the validation data.



(a) Shear strength

(b) Dilation

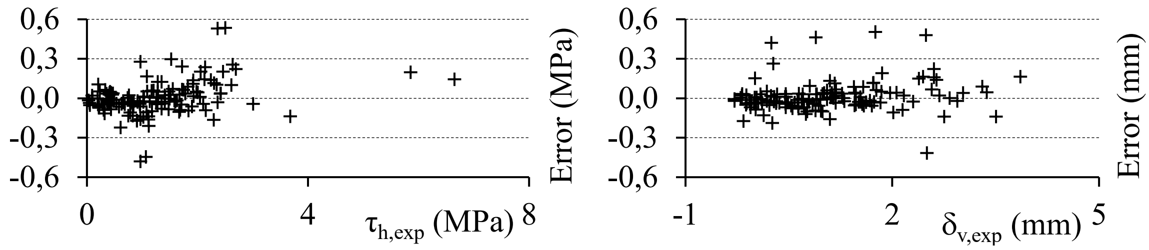
Figure 2. Influence of the normal boundary stiffness on the observed and predicted shear behavior.



(a) Shear strength

(b) Dilation

Figure 3. Influence of the initial normal stress on the observed and predicted shear behavior.



(a) Shear strength

(b) Dilation

Figure 4. ANFIS prediction errors.

It was evidenced that, except for some isolated data, the ANFIS offered good results for the various ranges of dilation values with absolute deviations smaller than 0.20 mm. Regarding shear strength, the largest deviations obtained were approximately 0.50 MPa. However, special attention should be paid to unfilled discontinuities in very soft rocks whose low shear strengths are more sensitive to deviations from the model predictions. Figure 5 shows a comparison between the ANFIS results and Papaliangas et al. (1993) tests in very soft rocks with σ_c of 3,5 MPa. The predictions of Dantas Neto et al. (2017) neuronal model are also shown, which presented good performance for this same experimental data set.

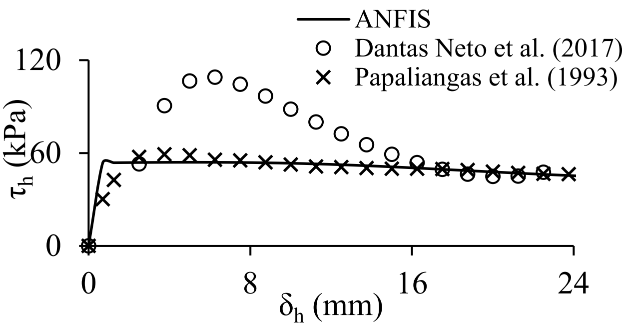


Figure 5. ANFIS performance in shear strength prediction for very soft clean rock joints studied by Papaliangas et al. (1993).

Even receiving little information about the behavior of discontinuities in very soft rocks due to the limitation of the data set used in its construction, the ANFIS reproduced excellent results in predicting the shear strength of discontinuities with these characteristics. It was proven that the neuro-fuzzy model proved to be more general than the neuronal model of Dantas Neto et al. (2017), which is not recommended for very soft discontinuities, because it overestimates the shear strength values, usually very low in discontinuities of this type. Therefore, it was possible to confirm the ability of ANFIS to explain, with good accuracy, the variation of τ_h and δ_v during the shearing process of unfilled rock joints.

Despite the proposed model delivering good results, it has some limitations, most of which are concerned with the distribution of input variables. ANFIS is limited by the domains of its input variables which are defined during its construction, i.e., its application is not yet recommended for scenarios with boundary conditions and joint properties that are outside its pre-established range of action. Nevertheless, the domains of its input variables can be adjusted as new data sets are available.

4 CONCLUSIONS

The proposed neuro-fuzzy model consists of two Adaptive-Network-Based Fuzzy Inference Systems with Takagi-Sugeno type inference process and consequents of their logic rules as linear equations for the prediction of the shear strength and its dilation respectively. They were developed using a robust dataset with 673 examples and defined based on previous studies that identified the main factors governing the shear behavior of unfilled rock mass discontinuities.

The ANFIS model can be considered a useful tool to model the shear behavior of unfilled discontinuities because it requires only some information about the characteristics of the discontinuities, the intact rock that constitutes their walls and the boundary conditions imposed on them, without the need for costly and complex laboratory tests. The results of the shear behavior prediction by the proposed model fitted very well to the experimental data used in its development.

It is important to mention that ANFIS model do not consider the effects of scale, weathering, water pressure, and drainage conditions in its predictions. Moreover, the main limitation of the proposed neuro-fuzzy systems are the domains of their input variables, which were defined during their construction. In this paper, they were constrained to the domain of the direct shear test measurements, although they can be adjusted as new data sets become available. However, even though the information provided by the 44 direct shear tests is not large enough to ensure a good generalization of the model, the great potential of ANFIS to solve problems involving complex phenomena was proven, when it is employed with a comprehensive and quality data set.

Finally, the main suggestion for future studies would be to use a larger data set to develop more general ANFIS model for unfilled rock joints, enabling their practical application in engineering problems. Another interesting alternative would be to adopt neuro-fuzzy techniques to predict the shear behavior of infilled rock joints.

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