A New Method for Predicting Indirect Tensile Strength of Sandstone Rock Samples

H. Fattahi*

Department of Earth Sciences Engineering, Arak University of Technology, Arak, Iran

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Subtractive clustering method
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Abstract

The tensile strength (σt) of a rock plays an important role in the reliable construction of several civil structures such as dam foundations and types of tunnels and excavations. Determination of σt in the laboratory can be expensive, difficult, and time-consuming for certain projects. Due to the difficulties associated with the experimental procedure, it is usually preferred that the σt is evaluated in an indirect way. For these reasons, in this work, the adaptive network-based fuzzy inference system (ANFIS) is used to build a prediction model for the indirect prediction of σt of sandstone rock samples from their physical properties. Two ANFIS models are implemented, i.e. ANFIS-subtractive clustering method (SCM) and ANFIS-fuzzy c-means clustering method (FCM). The ANFIS models are applied to the data available in the open source literature. In these models, the porosity, specific gravity, dry unit weight, and saturated unit weight are utilized as the input parameters, while the measured σt is the output parameter. The performance of the proposed predictive models is examined according to two performance indices, i.e. mean square error (MSE) and coefficient of determination (R2). The results obtained from this work indicate that ANFIS-SCM is a reliable method to predict σt with a high degree of accuracy.

1. Introduction

The tensile strength (σt) of rocks is an important parameter involved in the design of a variety of engineering structures. There are basically two approaches used for determining σt, one of which is to collect and test the rock specimens in the laboratory (direct methods), and the other one is to use the empirical equations and/or statistical methods (indirect methods) [1]. The direct standard method (assessment of σt in the laboratory) is time-consuming and expensive, especially with highly fractured and inhomogeneous rocks [2]. The difficulties associated with performing a direct uniaxial tensile test on a rock specimen have led to a number of indirect methods for assessing σt. Several pertinent studies have previously been undertaken in order to develop the empirical correlations to predict the σt values in terms of the physical/mechanical properties of rocks. The estimator variables used for predicting σt are the mineralogical composition and the intrinsic rock properties such as the electrical resistivity [3], grain size, aspect ratio, form factor [4], strength ratio, unconfined compressive strength (UCS), tensile crack initiation stress [5], total porosity [6], angle between the planes of rock anisotropy and the loading direction, diameter of the central hole, contact condition of loading [7] point load strength [6, 8], Shore hardness, sound velocity, Schmidt hardness, porosity, and point load index [9]. Although previous efforts are valuable, in many cases, the aforesaid empirical approaches are not capable of distinguishing the sophisticated structures involved in the dataset. These reasons have been the main causes of interest to better find out the interaction between the physical properties for the indirect prediction of σt of rocks. For this purpose, recently, the adaptive network-based fuzzy inference system (ANFIS) [10-12] has been
found to be a computational intelligence method that integrates the fuzzy inference system (FIS) concept into the artificial neural network (ANN), and has been widely used in the field of civil and mining engineering [13-15].

In a conventional FIS, the number of rules is decided by an expert who is familiar with the target system to be modeled. In an ANFIS simulation, however, no expert is available, and the number of membership functions (MFs) assigned to each input variable is chosen empirically, i.e. by plotting the datasets and examining them visually or simply by trial-and-error. For the datasets with more than three inputs and two outputs, the visualization techniques are not very effective, and most of the time, trial-and-error must be relied on. Generally, it is very difficult to describe the rules manually in order to reach the precision required with the minimized number of MFs when the number of rules is larger than 3. The better performance of ANFIS than the other intelligent methods is due to the FL and ANN combination. The path that an input would cover is like that of the input fuzzy inference system convey coordinates of sample to the input MFs, and then it passes through MF and changes; after that, its results go to the rules that according to available rules the category would be determined. One of the most important steps in the hybrid neuro–fuzzy modeling is the fuzzy membership value definition.

In this research work, the ANFIS-subtractive clustering method (ANFIS-SCM) and the ANFIS-fuzzy c-means clustering method (ANFIS-FCM) are suggested for the indirect estimation of \( \sigma_t \). In these models, porosity, specific gravity, dry unit weight, and saturated unit weight are utilized as the input parameters, while \( \sigma_t \) is the output parameter. The goodness of each hybrid model was evaluated using the data available in the literature. Finally, a statistical error analysis was performed on the modeling results in order to investigate the effectiveness of the proposed method.

2. Material and Methods

2.1. Adaptive network-based fuzzy inference system (ANFIS)

The ANFIS approach [16] is a combination of the neural learning and the Sugeno fuzzy to capture the input–output relationship. The structure of an ANFIS approach for two-input is presented in Figure 1.

**Figure 1. Structure of an ANFIS approach for two-input (after [16]).**

**Layer 1** is responsible for the fuzzification [17]:

\[
Q_i^1 = \mu_{A_i}(x) = \frac{1}{1 + \left(\frac{x - v_i}{\sigma_i}\right)^2},
\]

(1)

where \( \{\sigma_i, v_i, b_i\} \) is a series of parameters influencing the membership function (MF), \( A_i \) is the linguistic label, and \( x \) is the input.

**Layer 2** is [16]:

\[
Q_i^2 = W_i = \mu_{A_i}(x) \mu_{B_i}(y) \quad i = 1, 2
\]

(2)

**Layer 3** is as follows [16]:

\[
Q_i^3 = \bar{W}_i = \frac{w_i}{\sum_{j=1}^{2} w_j}, \quad i = 1, 2
\]

(3)

where \( w_i \) is the “firing strength” of the \( i \)th rule, which is computed in Layer 2.

**Layer 4** is as follows [17]:
Using different identification methods, and for a given dataset, different ANFIS models can be built. In this work, in order to identify the antecedent MFs, SCM, and FCM, two methods were used.

**2.2 Subtractive Clustering Method**

The mountain clustering method is simple and effective. However, its computation grows exponentially with the dimension of the problem. An alternative approach is the subtractive clustering method, introduced by Chiu [18], in which the data points are considered as the candidates for the center of clusters. The algorithm continues as follow:

Step 1: Consider a collection of $n$ data points \{\(X_1, X_2, X_3, \ldots, X_n\)\} in an M–dimensional space.

Step 2: After the density measure of each data point is calculated, the data point with the highest density measure is selected as the first cluster center. Let \(X_{c_1}\) be the point selected and \(D_{i_1}\) be its density measure. Next, the density measure for each data point \(x_i\) is revised as Equation (7):

\[
D_i = D_{i_1} - D_{i_1} \exp \left(-\frac{\|x_i - x_{i_1}\|^2}{\left(\frac{r_2}{2}\right)^2}\right)
\]

Step 3: After the density calculation for each data point is revised, the next cluster center \(X_{c_2}\) is selected and all the density calculations for the data points are revised again. This process is repeated until a sufficient number of cluster centers are generated.

**2.3. Fuzzy C–Means Clustering Method (FCM)**

FCM is a data clustering algorithm in which each data point belongs to a cluster to a degree specified by a membership grade; Bezdek introduced this algorithm in 1973 [19]. FCM partitions a collection of \(n\) vector \(X_i, i = 1, 2, ..., n\), into \(c\) fuzzy groups and finds a cluster center in each group such that a cost function of dissimilarity measure is minimized. The steps of the FCM algorithm are, therefore, first described in brief.

Step 1: Chose the cluster centers \(c_i, i = 1, 2, ..., c\), randomly from the \(n\) points \(\{X_1, X_2, X_3, \ldots, X_n\}\).

Step 2: Compute the membership matrix \(U\) using Equation (8):

\[
\mu_{ij} = \frac{1}{\sum_{k=1}^{c} (d_{ij})^{2/m-1}}
\]

where \(d_{ij} = \|x_i - x_j\|\), is the Euclidean distance between the \(i^{th}\) cluster center and the \(j^{th}\) data point, and \(m\) is the fuzziness index.

Step 3: Compute the cost function according to Equation (9). Stop the process if it is below a certain threshold.

\[
J(U, c_1, \ldots, c_c) = \sum_{i=1}^{c} J_i = \sum_{i=1}^{c} \sum_{j=1}^{n} u_{ji}^m d_{ij}^2
\]

Step 4: Compute the new \(c\) fuzzy cluster centers \(c_i, i = 1, 2, ..., c\), using Equation (10).

\[
c_i = \frac{\sum_{j=1}^{n} u_{ji}^m x_j}{\sum_{j=1}^{n} u_{ji}^m}
\]

Go to step 2.

**3. Experimental Database**

The main scope of this work was to implement the above methodology in the problem of \(\sigma_t\) prediction. The dataset applied in this work for determining the relationship among the set of input and output variables was gathered from the open source literature [20]. A database composed of the measured \(\sigma_t\) values and physical properties was established using the data collected from a formation around the Khuzestan Province (Iran). The 29 specimens of fresh sandstone blocks were cored in the laboratory. Each dataset contained the parameter...
porosity (%), specific gravity (Gs), dry unit weight (KN/m³), saturated unit weight (KN/m³), and measured σt (MPa). The σt values for the rock samples were determined using the Brazilian tensile strength tests. A detailed description of the database could be found in the referred resource [20]. Table 1 shows the statistical description of the datasets used in this work.

Table 1. Statistical description of the dataset utilized for construction of ANFIS models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Max.</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (%)</td>
<td>4.19</td>
<td>25.27</td>
<td>11.50</td>
</tr>
<tr>
<td>Specific gravity (Gs)</td>
<td>22.76</td>
<td>26.68</td>
<td>24.71</td>
</tr>
<tr>
<td>Dry unit weight (KN/m³)</td>
<td>16.97</td>
<td>24.62</td>
<td>21.90</td>
</tr>
<tr>
<td>Saturated unit weight (KN/m³)</td>
<td>19.42</td>
<td>25.11</td>
<td>23.04</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>0.19</td>
<td>13.23</td>
<td>5.90</td>
</tr>
</tbody>
</table>

4. Pre-Processing of Data and Performance Criterion

In order to start the training, the input and output data should be normalized to increase the efficiency of the networks in recognition of the relationships between the inputs and output data. Normalization is also really helpful in increasing the accuracy of the prediction and scaling the data to minimize the biasing of the networks. Data normalization can also reduce the time consumed for training. It is especially useful for modeling those applications where the input data is in different scales [21, 22]. There are many normalization techniques conventionally used to scale up the data including Z–Score normalization, Min–Max normalization, sigmoid normalization, statistical column normalization, etc. However, for the purpose of this work, the Min–Max normalization method was used. This was due to the capability of the Min–Max normalization in maintaining the variation in each feature after normalization. Beside, this normalization method can preserve all the relationships in the data [22]. The Min–Max normalization equation can be expressed as follows:

\[ x_M = 2 \left( \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \right) - 1 \] (11)

where \( x \) is the original value of the dataset, \( x_M \) is the mapped value, and \( x_{\text{max}} (x_{\text{min}}) \) denotes the maximum (minimum) raw input values, respectively . In addition to normalization, the mean square error (MSE) and coefficient of determination (R²) are two conventional criteria considered to assess the efficiency of the networks. MSE can be calculated using the following equation:

\[ MSE = \frac{1}{n} \sum_{k=1}^{n} (t_k - \hat{t}_k)^2 \] (12)

where \( t_k \) is the actual value, \( \hat{t}_k \) is the predicted value of the \( k^{th} \) observation, and \( n \) is the number of samples used for training or testing the network. MSE is routinely used as a criterion to show the discrepancy between the measured and estimated values of the network [23–26]. The coefficient of determination, R², can also be calculated as follows:

\[ R^2 = 1 - \frac{\sum_{k=1}^{n} (t_k - \hat{t}_k)^2}{\sum_{k=1}^{n} t_k^2 - (\sum_{k=1}^{n} \hat{t}_k^2 / n)^2} \] (13)

R² is widely used as a representation of the initial uncertainty of the model. The best network model, which is unlikely to build, would have MSE = 0 and R² = 1.

5. Results

The training and testing procedures of the two ANFIS models (ANFIS-SCM and ANFIS-FCM) were conducted from scratch for the five mentioned datasets. The MSE and R² values obtained for the training datasets indicate the capability of learning the structure of data samples, whereas the results of the testing dataset reveal the generalization potential and the robustness of the system modeling methods. The characterizations of the ANFIS models are revealed in Table 2.
Table 2. Characterizations of the ANFIS models.

<table>
<thead>
<tr>
<th>ANFIS parameter</th>
<th>ANFIS–SCM</th>
<th>ANFIS–FCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF type</td>
<td>Gaussian</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Output MF</td>
<td>Linear</td>
<td>Linear</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>207</td>
<td>157</td>
</tr>
<tr>
<td>Number of linear parameters</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Number of non-linear parameters</td>
<td>160</td>
<td>120</td>
</tr>
<tr>
<td>Total number of parameters</td>
<td>260</td>
<td>195</td>
</tr>
<tr>
<td>Number of training data pairs</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Number of testing data pairs</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Number of fuzzy rules</td>
<td>20</td>
<td>15</td>
</tr>
</tbody>
</table>

The number of rules obtained for the ANFIS-SCM and ANFIS-FCM models are 20 and 15, respectively. MFs of the input parameters for different models are shown in Figures. 2 and 3.

Figure 2. MFs obtained by the ANFIS–SCM model.
Figure 3. MFs obtained by the ANFIS–FCM model.
A comparison between the results of three models for the training and testing datasets is shown in Table 3. As it can be observed in this table, the ANFIS–SCM model with MSE = 0.016 and $R^2 = 0.9887$ for the testing datasets performs better than the ANFIS–FCM model for the indirect estimation of $\sigma_t$. Furthermore, correlations between the measured and predicted values of $\sigma_t$ for the testing and training phases are shown in Figures 4 and 5.

Table 3. A comparison between the results of the ANFIS models.

<table>
<thead>
<tr>
<th>ANFIS model</th>
<th>Training</th>
<th>Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANFIS–SCM</td>
<td>0.005</td>
<td>0.016</td>
</tr>
<tr>
<td>ANFIS–FCM</td>
<td>0.006</td>
<td>0.017</td>
</tr>
</tbody>
</table>

A comparison between the predicted values of $\sigma_t$ by the ANFIS models and the measured values for the datasets at the testing phases is shown in Figure 6. As shown in this figure, the results of the ANFIS–SCM model in comparison with the actual data show a good precision of the ANFIS–SCM model.
6. Conclusions

In this work, the indirect estimation of $\sigma_i$ was investigated using two ANFIS models (ANFIS-SCM and ANFIS-FCM), and the following conclusions could be drawn:

- Porosity, specific gravity, dry unit weight, and saturated unit weight were incorporated for the indirect estimation of $\sigma_i$ of rocks.
- A comparison was made between two ANFIS models (ANFIS-SCM and ANFIS-FCM) using 29 data samples and based upon the performance indices MSE and $R^2$. ANFIS–SCM with MSE = 0.016 and $R^2 = 0.9887$ was selected as the best predictive model.
- The generalized Gaussian MFs were used in the present models. MFs were tested. It is important to mention that the rules used are generally based on the model and variables that are dependent on the user’s experience and the trial-and-error method. Furthermore, the shape of MFs depends on the parameters involved, and changing these parameters will change the shape of MF.
- Consequently, one may conclude that ANFIS–SCM is a reliable system modeling technique for predicting $\sigma_i$ of rocks with a highly acceptable degree of accuracy and robustness.
- This work shows that the ANFIS approach can be applied as a powerful tool for modeling some of the problems involved in mining and civil engineering.

References


یک روش جدید برای پیش بینی غيرمستقيم مقاومت کششی نمونه‌های سنگی ماسه سنگ

هادی فتاحی
گروه مهندسی زئوکامیک، دانشکده مهندسی علوم زمین، دانشگاه صنعتی اراک، ایران
ارسال 10/05/2020، پذیرش 22/05/2020
h.fattahi@arakut.ac.ir

چکیده:
مقاومت کششی یک سنگ نقش مهمی در ساخت ایمن سازه‌های مختلف عمرانی مانند پی بس، اتو ناوبری و خطری‌ها دارد. از طرفی برای برای پروردهای خاص تغییر مقاومت کششی در آزمایشگاه می‌تواند پرهزینه، مشکل و زمان‌زاشد. بیشتر مسائل بین شده در پروسه آزمایشگاهی معمولاً مقاومت کششی به صورت غیرمستقیم ارزیابی می‌شود. در این تحقیق، استنتاج و تطبیق نوروزی (افس) برای ساخت مدل جهت پیش‌بینی غیرمستقیم مقاومت کششی نمونه‌های سنگی سناک استفاده کرده است. در این تحقیق و مدل افیس به نام افیس-خوشنده کاهشی و افیس-سی-مینز فاری ساخته شده است. مدل‌های افیس مذکور بر روی داده‌های موجود از منابع قبل در مدل‌های گذشته کارگرده شده و در این مدل‌ها، نخل، وزن مخصوص، وزن مخصوص خشک و وزن مخصوص اشباع به عنوان ورودی و مقاومت کششی به عنوان خروجی مورد استفاده قرار گرفت. در این مدل‌ها تغییرات در شاخص میانگین خطای مربوط و ضریب تغییر استفاده شد. نتایج بدست آمده از این تحقیق نشان می‌دهد که افیس-خوشنده کاهشی یک روش قابل اعتماد و با درجه دقت بالا برای پیش‌بینی مقاومت کششی است.

کلمات کلیدی: مقاومت کششی، خواص فیزیکی، سیستم استنتاج تطبیقی نوروزی، روش خوش‌نده کاهشی، روش سی مینز فاری.