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SIMULATION OF DILATOMETER TESTS BY NEURAL NETWORKS

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Abstract- Rock rigidity may be experienced in a wide range depending on several factors, and different methods can be used to consider their load-deformation behaviors. In this context, dilatometer tests (DTs) can be applied to obtain the modulus of elasticity of rock masses; therefore, it is possible to evaluate in-situ stress-strain behavior of rock masses realistically. Nevertheless, the application of this test is expensive as well as time-consuming, and necessitates mobilization of the equipment to construction site by trucks. The aim of this study is to simulate the load-deformation curve obtained of DT by neural networks (NNs). Therefore, the dilatometer test can be modeled as well as synthetic simulation of the test enables analyzers to characterize the material behavior. In order to investigate this, 50 different stress-deformation curves are obtained from DTs conducted on limestone formation underlying a dam (Dim dam) construction site in the Southern part of Turkey. The developed database by the curves was used for training and testing of the NN models. The results revealed that NN technique is quite successful for modeling the stress-deformation behavior of specific rocks based on DT results. It is therefore possible with the help of this alternative tool developed for the simulation of DT i) to model DT numerically, ii) to simulate the stress-strain behavior successfully, iii) to calculate the modulus of deformation efficiently, iv) to generate additional DT data synthetically, v) to develop material model alternatively, and vi) to make assumptions on the characterization of the rock mass behavior using previous information gathered by DTs..
Key Words- Stress-deformation curve, neural networks, dilatometer test, simulation.

1. INTRODUCTION

Foundations on problematic rocks and should a) possess high bearing capacities for carrying the infrastructure as well as b) rotate and/or displace below a predefined criteria, which is related with the type of the foundation. Analogous principles are valid for several engineering designs such as tunnels and slope retaining structures. Therefore, viable structures can be constructed solely considering these basic engineering principles. Stress-strain calculation of a structure requires unique information on the rigidity of the material such as modulus of deformation, which is the fundamental parameter for the characterization of the deformability.

Investigation of the studies in the literature led to the conclusion that majority of the studies concern the use of flat dilatometer, which is particularly useful for sands, silts and clays, where the grains are small compared to the membrane diameter [1, 2]. Essentially, comparisons of DT with other in-situ tests have attracted attention of a number of researchers. Iwasaki et al. [3] have compared dilatometer test results with laboratory test findings. The authors mentioned that the undrained strength and the constrained modulus by Marchetti's methods [4] agree with the triaxial and oedometer test findings. Larsson and Åhnberg [5] have reported the inconsistencies of a number of field tests, including DT. The authors have indicated the various effects of overconsolidation on the field vane, cone penetration and dilatometer test results. Apart from these, standard and seismic dilatometers can be used for evaluation of liquefaction potential of sand layers [6-9]. The DMT is effective for the settlement analysis of compacted fills [10] and shallow foundations [11]; also for determination of consolidation characteristics [12]. Evaluation of dilatometer tests and modeling related with the in-situ measurements has been in the research area of numerous engineers. In this context, Ito et al. [13] have developed a new method for the evaluation of dilatometer measurements. Circumferential deformation of the boreholes is utilized for the determination of borehole pressures. The re-opening pressure is useful for the determination of maximum horizontal stress. Gokceoglu et al. [14, 15] have developed empirical equation and neuro-fuzzy modeling using dilatometer test results on rock masses. Sonmez et al. [16] developed some empirical equations for estimation of deformation modulus of both intact rocks and rock masses using both dilatometer and plate loading test results. Palmström and Singh [17] have compared the methodologies for the determination of deformation modulus of rock masses, and made an adjustment to Goodman Jack test results, regarding to Plate Loading Tests. Georgiadis and Michalopoulos [18] have used dilatometer test results for the design of grouted piles in rock. Littechild et al. [19] have utilized Goodman Jack, Pressuremeter test results, as well as the geotechnical studies in the field for an initial comparison and discussion of these methodologies. A modified Rock Mass Rating is also proposed by them.

On the other hand, modeling of loading/unloading curves depending on pressure-deformation variation is crucial for material science and many engineering problems. Several design parameters, especially the rigidity of the material, can be obtained via these curves. The deformation modulus that is calculated by stress-strain curve of DT test is the essential parameter of the structural analyses performed on formations related with the engineering structure. The modulus of any part of the stress-strain curve can be calculated from the test results by a modeling tool that is capable of simulating the behavior. As a result of any reason, such as the time consuming as well as transportation required attribute of the test, there may be a requirement to simulate the incomplete data. Furthermore, another completion requirement may be arisen from an event which is misfortune during the application of the test. In this study, an alternative tool is developed for the simulation of DT i) to model DT numerically, ii) to simulate the stress-strain behavior successfully, iii) to calculate the modulus of deformation efficiently, iv) to generate additional DT data synthetically, v) to develop material model alternatively, and v) to make assumptions on the characterization of the rock mass behavior using previous information gathered by DTs.

2. MATERIALS AND METHODS

Various geotechnical and geological experiences can be gained by tunnel engineers during the excavation process of the projects. Obviously, each tunnel has different problems based on the existing uncertainties in geological conditions [20]. Heterogeneity, high deformability, and low strength of soft rock masses can be exemplified as major difficulties in predicting the structural performance of a tunnel.

Therefore, effective techniques and specific data are needed to solve the instability problems under such circumstances [21-23].

The Goodman dilatometer test (GDT) is suitable for fractured rock masses. During the test, pressure is applied to the walls of borehole of 76.2 mm. diameter via a steel probe, and the surface deformations are measured at certain periods (Figure 1). The expansion of the probe by deforming the rock in the borehole is recorded in the precision level of 1/100 mm. Movable plates are used to transfer the load from device to rock walls. Each of the movable plates is supplied with two LVDTs. During the experiments, a 12-cylinder 52101 type probe with the maximum pressure of 64 MPa is utilized. The jack extension and pressure ranges are 11.4 mm. and 64 MPa, respectively. The most important point here is that the test does not necessitate direct access to rock or soil face [24]. The test has some limitations: a) it was assumed that the rock mass is linearly elastic, isotropic and homogeneous b) The compressive and the tensile strength of rock mass are equal. c) The volume of the rock mass in charge is not capable of simulating the discontinuities on the whole mass. The test results should carefully be corrected in order to prevent low elastic moduli measurements [25].

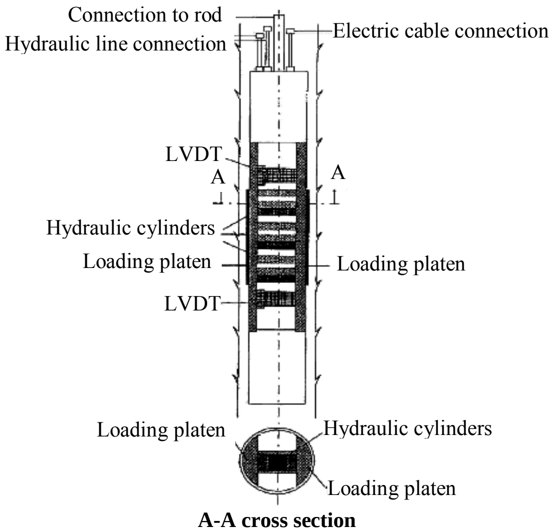

Figure 1. The Goodman Jack Apparatus [26].

The tests are employed beneath the construction site of Dim Dam Power Tunnel, which is located at the north-east of Antalya city, Turkey. The geologic units in the investigation area consist of Paleozoic aged metamorphic rocks, which consist of mica schist, chloride schist, graphite schist, and limestone. In the area covered by Alanya, Massif three superimposed nappes (Alanya Nappes) were differentiated within the crystalline Alanya Massif. Nappes, which are Yumrudağ, Sugözü and Mahmutlar Nappes, tectonically overlie the predominantly sedimentary rocks belonging to the Antalya Units. The Alanya Nappes have a gently (<35º) undulating, but largely northerly, regional dip. Dim River Dam and its reservoir area are largely located on recrystallized limestone of the Yumrudağ Nappe. The Yumrudağ Nappe consists of schists overlain by a thick sequence of recrystallized limestone. The passage from the schists to the overlying carbonates is gradational with schist and carbonate bands several meters thick at the contact. Pelites, psammites, calc-schists, meta-dolomites and thin recrystallized limestone bands are the major lithologies of the schist unit [27]. Dim River Dam, which is located on Yumrudağ Nappe, is situated on a sequence consisted of chlorite schist-graphitic schist and recrystallized limestone. During the excavation of energy tunnel, these lithologies above mentioned were met. Recrystallized limestones have a jointed structure and include karstic voids. These voids mostly fill limestone gravels and red colored soft clays. [28].

The investigated tunnel was designed with an 8.65 m^2 horse-shoe section to accommodate a 4.25m in diameter single tube. The tunnel lies at a relatively shallow depth (the depth to the ground surface elevation from the design level of the tunnels varies from about 20–70 m). The rock mass strength parameters at the location were determined by B5 which is the representative borehole in the study. Consequently, the moduli of deformation of the rock mass have been obtained by dilatometer tests. The tests were carried out on the tunnel segments in which significant instabilities and failures were observed (3+810km.–4+010 km.) and karstic problems (4+166 km.–4+174 km.) encountered during the power tunnel excavations.

At the end of the dilatometer tests, the pressure applied in two directions enable the user to measure the surface deformations. The GDT provide total deformation of the rock mass, its elastic and plastic deformation, Modulus of Elasticity as well as total and elastic moduli. A part of data obtained is given in Table 1. In addition, the pressure-deformation curves give detailed information about the deformation moduli. A pressure deformation curve is given in Figure 2.

Table 1. Some geotechnical parameters obtained from laboratory and in-situ tests.

Boring No	STA(km)	Dilatometer Test	Laboratory Tests		
		Modulus of Elasticity, E (GPa)	Modulus of Elasticity, E (GPa)	Poisson Ratio, ν	Unconfined Comp. Strength, c_u (MPa)
B1	0+104	50	300	0.25	44
B2	2+575	100	230	0.30	48
B3	3+200	100	-	0.30	-
B4	3+903	20	-	0.33	-
B5	3+985	20	-	0.33	-

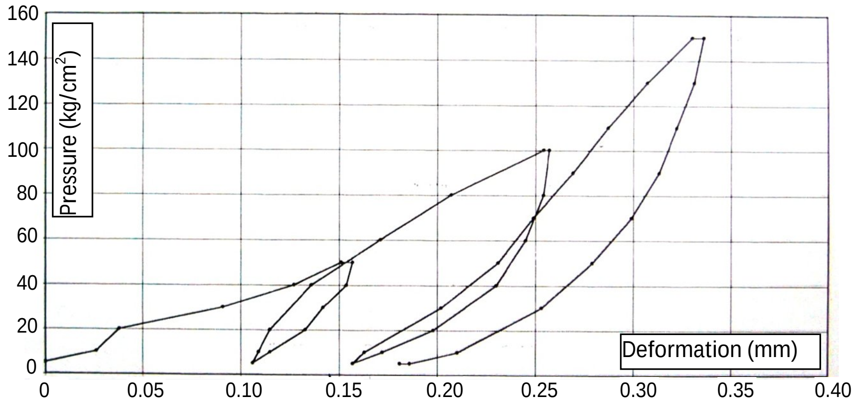

Figure 2. An example of Goodman Jack dilatometer result.

3. NEURAL NETWORKS

Neural networks (NNs) are probably the most popular numerical tools, which simply imitate the human's nervous system. The networks consist of input, hidden and output layers, as well as steepest descent algorithm and generalized delta rule are generally used in this methodology. The primary advantage of NNs is its learning and simulating ability of training patterns in supervised manner. The basic element of a BPNN is the neuron (or perceptron), which produces output signal using following formulation:

$$y_k = \varphi(v_j) = \varphi\left(\sum_{i=1}^{n} x_i\, w_{ij} - b_j\right) \qquad (1)$$

where, x_i is input signal, w_{ij} is synaptic weight, b_j is bias value, v_j is induced local field, φ is activation function, y_k is output signal, n is the number of neurons for previous layer, and k is the index of processing neuron. In order to make the output converged to a certain range, an activation function must be used. Formulation of hyperbolical tangential function is as follows:

$$\varphi(x) = \tanh(x) \qquad (2)$$

In order to measure the success of the network, an error function is defined. Formulation of the sum of square error function is given below:

$$E = \frac{1}{2}(y_i^2 - T_i^2) \quad for\ i = 1 : z \qquad (3)$$

where, z is the number of output nodes, y is the outcomes of the network and T is the formerly known target values of the dataset. After the calculation of the error, computed error is distributed "backwards" to the hidden and input layers using steepest decent algorithm by the following formulation:

$$\Delta w_n = \alpha \Delta w_{n-1} - \eta \frac{\partial E}{\partial w} \qquad (4)$$

In this equation, Δw_n and Δw_{n-1} are the weight change in n^{th} and $(n-1)^{th}$ iterations, α is the momentum factor stabilizing weight change alterations and η is the learning rate parameter, which is expected to decrease as the iteration number increase [29]. It should be noted that, before beginning the training process, input data should be normalized:

$$x_i = \frac{x_{ui} - \min(x)}{\max(x) - \min(x)} \qquad (5)$$

where, x_{ui} is an element of input data set, x_i is the normalized x value, *min(x)* and *max(x)* are the minimum and maximum of input data sets, respectively. NNs are widely known and popularly utilized techniques for last two decades; therefore, no further information on them will be given here.

4. SIMULATION OF DILATOMETER TESTS BY NN

As widely known, a material model can be used either to predict/verify the observed behavior after testing process or to estimate the behavior of untested or non-modeled materials. In this respect, a constitutive model is a kind of the simulation of the material's stress-strain relationship, and a modeling effort of stress-strain data obtained by several tests on the material. In this study, it is decided to teach the relationship between stress (input) and strain (output) data to NN model to model the path-dependant stress-strain behavior of the material that was measured by GDT. While the input layer consists of three consequent pressure (stress) readings and (p_{n-1}, p_n, p_{n+1}) and the former deformation reading (δ_{n-1}), the latter deformation reading (δ_n) is selected as the output parameter which will be estimated by the NN model later. Therefore, it is aimed to teach the preceding deformation value by use of the former value and the pressure readings. Simple schematic illustration of this methodology is explained in Figure 3 [29].

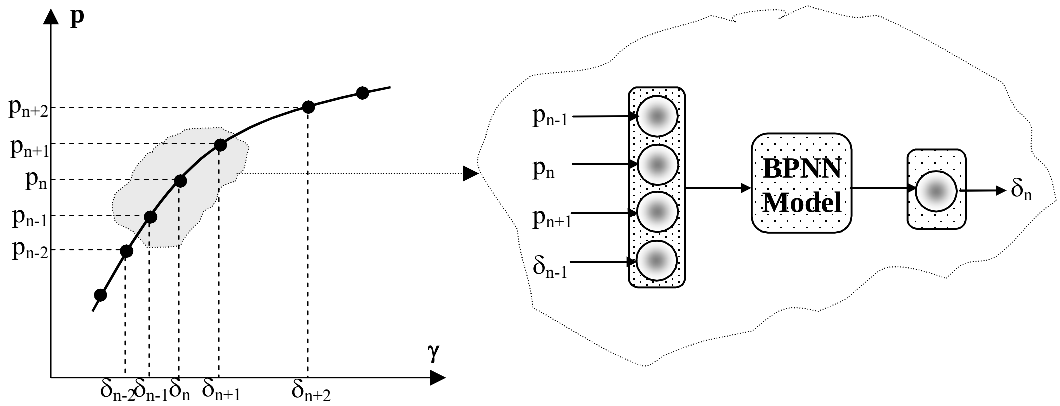

Figure 3. Schematic illustration of BPNN based material modeling philosophy.

Under the light of the methodology explained above, the results of 50 GDTs, which performed on limestone formation, are utilized to train the network. Each test data is processed to the network separately using batch training technique. It should be noted for preprocessing session that the input/output patterns are normalized using Eq.5, as well as the synaptic weights are selected randomly from normal distribution. The backpropagation algorithm, which using Widrow-Hoff (delta) learning rule as well as steepest descent optimization technique is utilized to train the NN models. In addition, sum of square error energy function (Eq.3) is preferred to calculate the performance of the network. Finally, one hidden layer is selected, and the number of hidden neurons is determined by trial-and-error approach Fig. 4). Referring to Figure 4 again, the hidden layer number is kept between 10 and 70 neurons, and regarding to the results of the training sessions, an optimal mean square error is obtained for 50 hidden neurons. Schematic illustration of NN models utilized to model the stress-strain relationship is given in Figure 5. It should be noted that, for hidden layer number more than 50 overtraining is observed. In order to avoid the overtraining and the inefficiency of larger hidden layers, no more trials are performed for more than 70 hidden neurons. On the other hand, during the trial-and-error analyses, overestimating and underestimating problems are also considered for intermediate as well as smaller hidden layer sizes, such as 5, 20, and 40. Nevertheless, the results are consistent with the findings, and selected hidden layer size is found to be optimum in terms of optimization and calculation complexity.

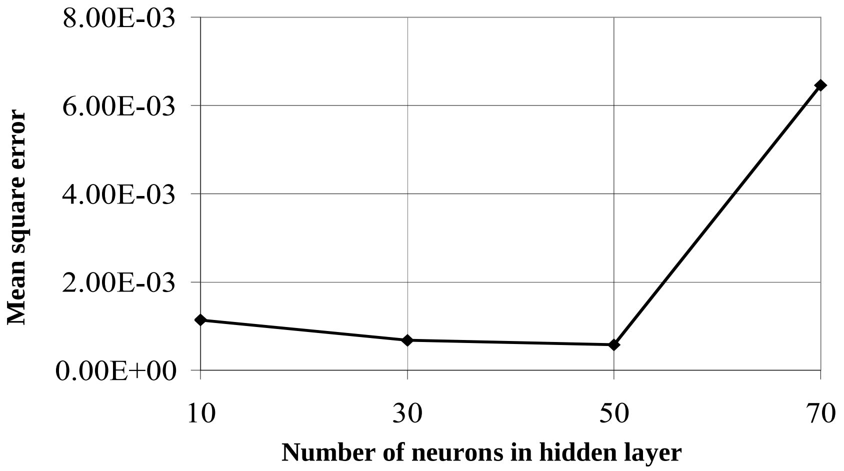

Figure 4. Effect of hidden neurons on the network's performance.

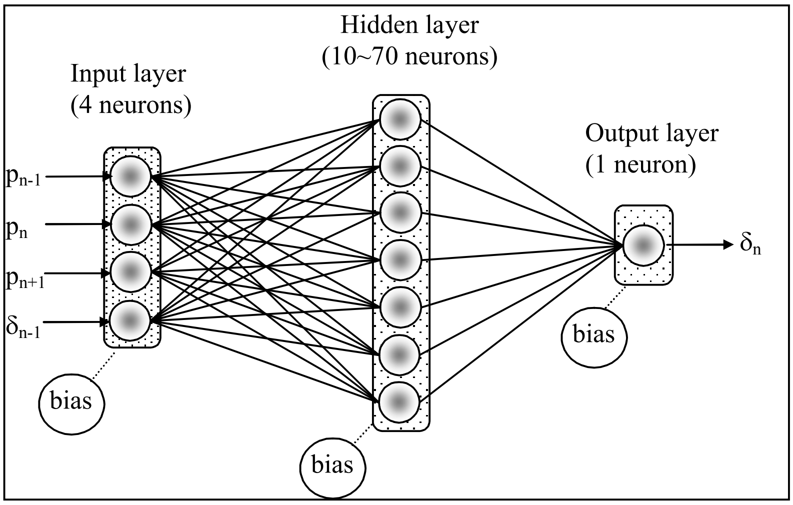

Figure 5. Network setup for dilatometer test result evaluation.

After the completion of training sessions that were performed with 50 different test data, resulting NN model is tested with two different test data that was never used in the training sessions. Results denoted that the NN model relevantly characterized the stress-deformation behavior. The scatter plot of the calculated and actual deformation values are given in Figure 6. Furthermore, R^2 values of 0.963 and 0.955 show that the model is superior for the estimation of the deformation values obtained by dilatometer tests. Actual stress-deformation path and the path obtained by the model are shown in Figures 7a and b. It can easily be derived from Figure 8 that, BPNN model can successfully simulate GDT data using the information gathered from the identical test field (for same rock formation and properties), and be used for the prediction of the missing data.

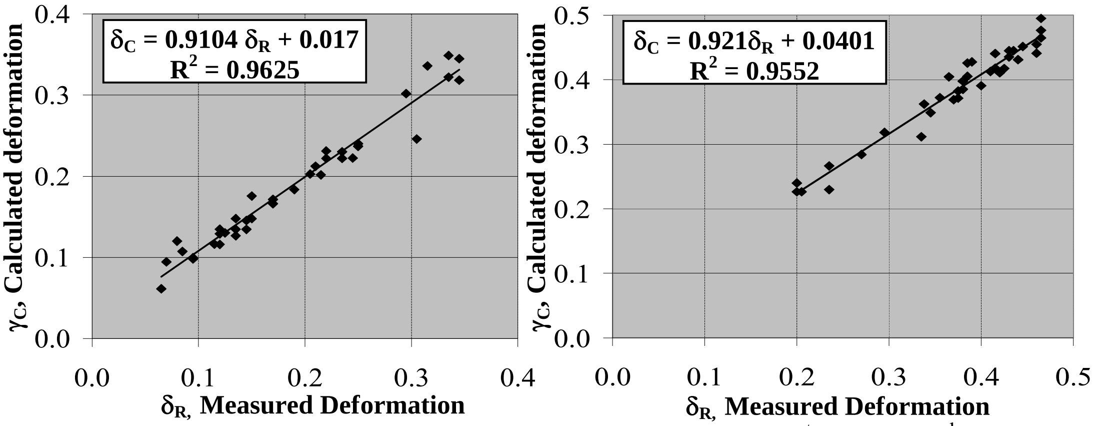

Figure 6. Calculated and measured deformations (a) 1st test (b) 2nd test.

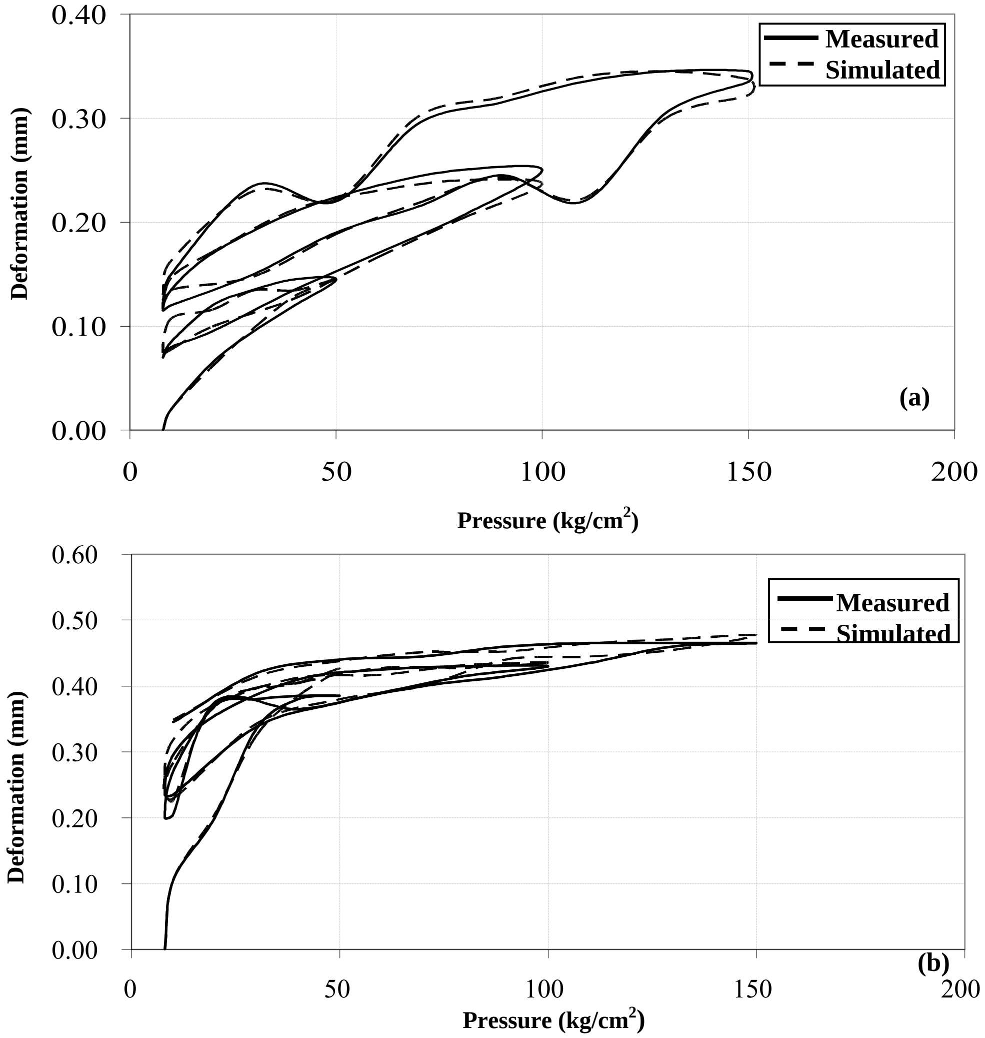

Figure 7. Calculated and measured deformations (a) 1st test (b) 2nd test.

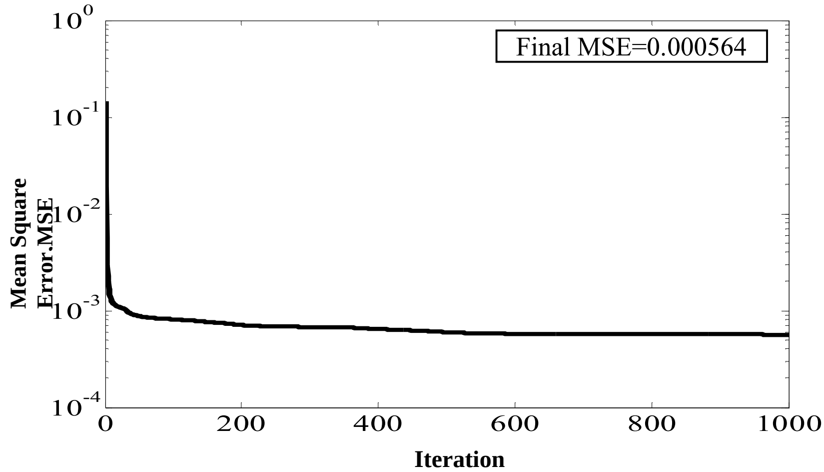

Figure 8. Learning graph indicating objective function value for the BPNN model.

5. CONCLUSIONS

In this study, it is investigated whether the dilatometer tests employed on specific soft rocks can be modeled by NN methodology. Results showed that NNs are successful for modeling the stress-deformation behavior of specific rocks. In this respect, an alternative tool is developed for the simulation of DT numerically. It is therefore possible with the help of this alternative tool developed for the simulation of DT i) to model DT numerically, ii) to simulate the stress-strain behavior successfully, iii) to calculate the modulus of deformation efficiently, iv) to generate additional DT data synthetically, v) to develop material model alternatively, and v) to make assumptions on the characterization of the rock mass behavior using previous information gathered by DTs.

In essence, the calculation of the average deformation modulus could be preferable for most of the practitioners. Nevertheless, to have chance to complete the strain-stress curve when some of points are not available or to simulate the stress-strain curve successfully, instead of a complex constitutive equation, can be very promising for practical and theoretical studies. In this context, such a NN model can be incorporated into a numerical model using finite element or discrete element analyses.

On the other hand, NN methodology is capable of successful learning, the reason why they are usually referred to as universal approximaters; however, NN-based simulation model for rock analyses may not yield successful results for different rock mass types. Because the input data used for training characterizes unique tock behavior valid for tested specimens. Therefore, it is compulsory to consider rock behaviors differently, and not try to generalize all rock types using single NN-model. In simple words, NN models are data-driven techniques which should be aimed to characterize the properties valid for test samples under certain conditions. In this manner, the engineering behavior of each rock formation should be considered separately.

It should be mentioned that, NN based models neither include any constitutive behavior nor any material property. They can only learn the behavior characterized by training pattern; therefore, results are highly dependent to the quality and the quantity of the data. It must be considered as powerful tool for modeling the relationship between the input and output data, and can produce outcomes with respect to the quality of training data. In this respect, determination of the input/output parameters and the quality/quantity of the database are crucial for a more accurate modeling of the deformation/pressure behavior.

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