International Journal of Neural Networks and Advanced Applications
DOI: 10.46300/91016.2022.9.3 Volume 9, 2022

Preliminary Design of Seismic Isolation Systems Using Artificial Neural Networks

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Abstract— This works attempts to implement artificial neural networks (ANN) for modeling Seismic-Isolation (SI) systems consisting of Natural Rubber Bearings and Viscous Fluid Dampers subject to Near-Field (NF) earthquake ground motion. Fourteen NF earthquake records representing two seismic hazard levels are used. The commercial analysis program SAP2000 was used to perform the Time-History Analysis (THA) of the MDOF system (stick model representing a realistic five-story base-isolated building) subject to all 14 records. Different combinations of damping coefficients (c) and damping exponents (α) are investigated under the 14 earthquake records to develop the database of feasible combinations for the SI system. The total number of considered THA combinations is 350 and were used for training and testing the neural network. Mathematical models for the key response parameters are established via ANN. The input patterns used in the network included the damping coefficients (c), damping exponents (α), ground excitation (peak ground acceleration, PGA and Arias Intensity, Ia). The network was programmed to process this information and produce the key response parameters that represent the behavior of SI system such as the Total Maximum Displacement (DTM), the Peak Damper Force (PDF) and the Top Story Acceleration Ratio (TSAR) of the isolated structure compared to the fixed-base structure. The ANN models produced acceptable results with significantly less computation. The results of this study show that ANN models can be a powerful tool to be included in the design process of Seismic-Isolation (SI) systems, especially at the preliminary stages.

Keywords— seismic, base-isolation, supplemental viscous damping, near-field, ANN.

I. INTRODUCTION

The main objective of designing BI system for any structure is to guarantee the functions for which it was built by maintaining its functionality and its structural integrity. The structural control is based on models that used to predict the behavior of a structure. In general, it is interesting to find out how changes in the input variables affect the values of the response variables. ANN approaches have potential value for predicting the behavior of the SI systems.

Seismic-Isolation (SI) with and without supplemental damping for energy dissipation has proven to be an effective method of control for structures during seismic events. Many researchers investigated the use of different types of isolators see for example [1]-[14]. When faced with the challenge of limiting the Total Maximum Displacement (DTM) to practical limits, especially in NF sites, often times the designer would rely on Viscous Fluid Dampers (VFDs). Once supplemental damping is deemed necessary, many designers would prefer utilizing the linear behavior of NRB isolators combined with the supplemental damping provided by VFDs. This system has also been used in many projects in the USA and Japan [15]-[20]. This work utilized ANN to model the behavior of the combined NRB-VFD system under dual-level ensembles of 14 NF earthquake motions. To develop the database of feasible combinations for the SI system, the overall SI system performance is evaluated, for different combinations of damping coefficients (c) and damping exponents (α), under the 14 earthquake records. For that purpose, a Multi-Degree-Of-Freedom (MDOF) system is adopted and the commercial analysis program SAP2000 [21] was used to perform the Time-History Analysis (THA). The key response parameters considered are the DTM, the Peak Damper axial Force (PDF) and the Top Story Acceleration Ratio (TSAR) of the isolated structure compared to the fixed-base structure. The total number of considered THA combinations is 350 and were used for training and testing the neural network. The input patterns used in the network included the damping coefficients (c), damping exponents (α), ground excitation (peak ground acceleration, PGA and Arias Intensity, I_a). Mathematical models for the key response parameters are established via ANN.

II. MODEL DESCRIPTION

A. The damping system

The fluid viscous damper force-velocity behavior is governed by the mathematical expression described in Eqn (1):

$$F_D = c\,\mathrm{sgn}(\dot{v})\left|\dot{v}\right|^{\alpha} \tag{1}$$

where FD is the damper force (kN), c is the damping coefficient (kN-(s/m)$^{\alpha}$), v is the damper extensional velocity (m/s), α is the velocity exponent (for a linear damper, α =1) and sgn denotes signum function describing the velocity sign. In seismic applications, nonlinear dampers with damping exponent less than unity are preferred due to their softening or yielding nature at higher velocities and the stiffening effect at lower velocities. This nonlinear characteristic results in significant reduction of base displacement in response to strong ground shaking, particularly in NF situations. Furthermore, it puts practical limitations on the amount of force transferred to the structural elements. Although some manufacturers can produce dampers with a value as low as 0.1, the typically used values range from 0.4 to 0.7. In this study, the damping exponent values considered range from 0.4 to 1.0 with intermediate values equally spaced at 0.15 intervals. Except when $\alpha=1$, the damper elements are behaving nonlinearly and they are the only part of the model that could exhibit nonlinearity. The superstructure of an isolated structure is typically expected to remain near-elastic throughout significant seismic events, which justifies the linear analysis here. The considered values for the damping coefficient c range from 175 to 525 kN-(s/m)$^{\alpha}$ with intermediate values equally spaced at intervals of 88 kN-(s/m)$^{\alpha}$. The five different c and α values are used to generate 25 combinations to be investigated in the analysis.

B. SAP2000 modeling of the MDOF system

To include higher modes influence in the base isolation behavior, MDOF systems should be considered. The numerical analysis of the proposed MDOF system was conducted using the commercial finite element code SAP2000 (CSI 2010) [20]. For this study, a simple lumped-mass stick model is used to represent a five-story base-isolated building which has been introduced by Kelly et al. [22]. The building structural parameters and isolator properties are proportioned such that the fundamental period of vibration is 2.5 s and the modal damping is 5% of critical. The MDOF system has been modeled in three different configurations (boundary conditions) for comparison: (1) fixed base, (2) isolated without dampers, and (3) isolated with dampers. Figure 1 shows the SAP2000 model used to model the MDOF system.

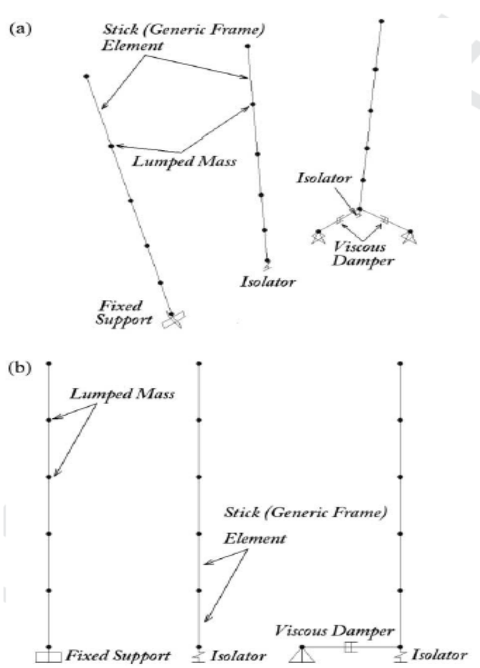

Fig. 1. SAP2000 MDOF Model

C. The ground excitation

There are different parameters to characterize and quantify earthquake demand and damage potential. The Peak Ground Acceleration (PGA) and Arias Intensity (I_a), first introduced by Arias [23], are good examples of such parameters. The Arias Intensity (Ia) is adopted here as the main descriptor of the ground motion excitations for its ability to capture the earthquake amplitude variation, frequency content and duration. The Arias Intensity can be computed using the following Eqn (2):

$$I_a = \frac{\pi}{2g}\int_0^t a(t)^2 dt \tag{2}$$

where $\alpha(t)$ is the ground acceleration history in g's, and g is the gravitational acceleration.

III. Results and discussion

A. Time-history analysis

The commercial analysis program SAP2000 was used to perform the Time-History Analysis (THA) of the MDOF system subject to all 14 records. The analyses were performed for all three MDOF systems representing the benchmark fixed-base, as well as the isolated buildings with and without dampers. For each of the records, three key response parameters were considered: the DTM, the Peak Damper Force (PDF) and the TSAR at the isolated and the fixed structures. The results for the three response parameters when the 25 different combinations of damping coefficients and damping exponents are investigated under the 14 earthquake records consist of 350 (5 c values×5 α values×14 records) THA combinations. The THA data set is further divided into two subsets: Set 1, consisting of THA results from 300 (c, α, EQ) combinations is used to produce mathematical models via MRA and ANN; Set 2, consisting of THA results from 50 (c, α, EQ) combinations is used to test the developed mathematical models. It should be emphasized here that the data from 50 testing combinations were not included in the modeling phase.

B. Neural Network (NN) Analysis

The primary objective of this section is to present a computer oriented method based on artificial neural networks (ANNs) technology to assess the structural behavior of BI systems. It is basically made up of a computer empirical model that maps the output variable or target value (DTM, PDF, TSAR) directly to a set of input variables (C, α, PGA, Ia) thus deducing a functional relationship for prediction purposes. The data utilized in this study were initially generated by a commercial analysis program SAP2000. The advantage of proposed ANNs model over *SA*P2000 computer programs is that it requires minimal

DOI: 10.46300/91016.2022.9.3

input data with minor intermediate computations.

Neural networks analysis is an information processing technique in which a neuron is the main element and it is an operator with inputs and outputs, associated with a transfer function, f , called a "sigmoid" interconnected by synaptic connections or weights, w (plus a bias). Fig. 2 illustrates how information is processed through a single neuron. The way in which inputs are combined, how the resulting internal activation level is used to produce an output, and the way in which weights and biases are changed (the learning rule) are collectively called network architecture (see Fig. 3) results in a network paradigm. Several network paradigms are commonly involved with each designed to solve specific kinds of problems.

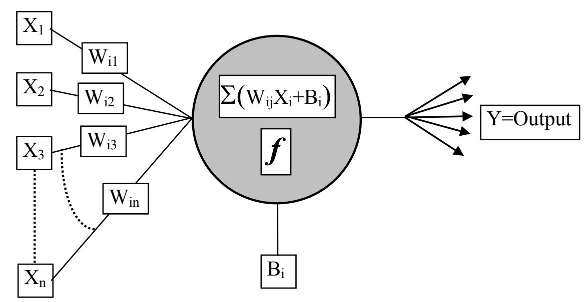

Fig. 2. Schematic of a single neuron

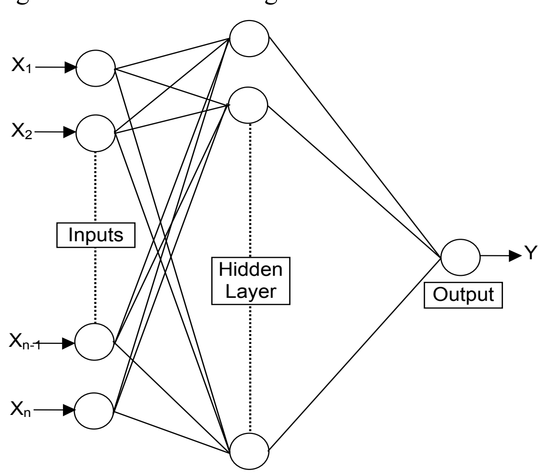

Fig. 3. Typical neural networks architecture

C. *Network Model and Architecture*

The mapping of the inputs to the outputs (target values) is established through the neural net architecture. For the problem considered here, the following architecture was considered: feed-forward network with 5 hidden neurons, 3 output neurons, tansig hidden neurons and linear output neurons. Weights and biases joining the input nodes to the hidden nodes, and those bridging this latter node to the output node were initially assigned randomly see Fig.4.

D. *Neural Networks Solution of BI Systems*

The NN model considered consists of an input layer with 4 input parameters to represent the (C, α, PGA, Ia)), an output layer with 3 output parameters to represent the (DTM, PDF, TSAR) and one hidden layer with 5 neurons, as can be seen in

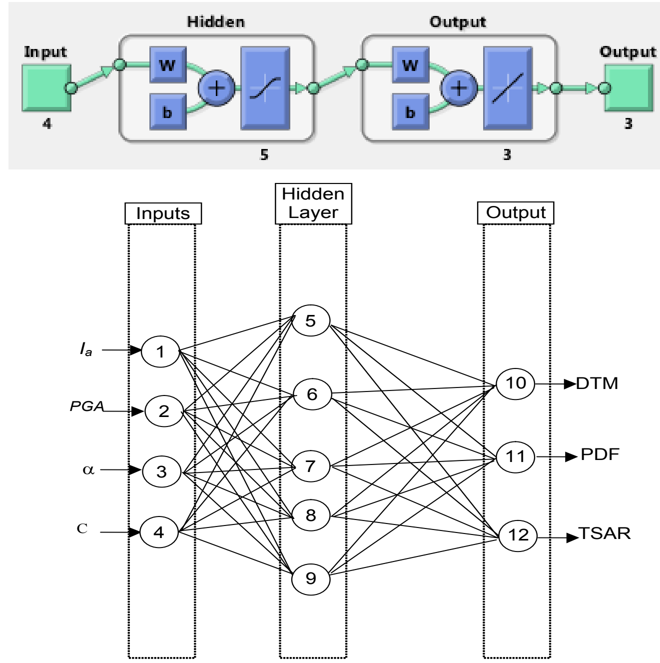

Fig. 4. Neural networks architecture

Fig. 4. Every neuron in the network is fully connected with each neuron of the next layer. The most appropriate model was sought by training the artificial neural networks with 3, 5, and 7 hidden nodes. The progress of the networks' training was monitored by observing the output error after each training cycle. The results showed that the average sum squared error decreased with increasing number of hidden nodes. Fig. 5 shows the training progress of the final network with 5 hidden nodes. The asymptotic shape of the curve implies that the network learning was notably complete by the end of the training. Furthermore, Fig. 5 indicates that approximately 51 Epochs were required for convergence.

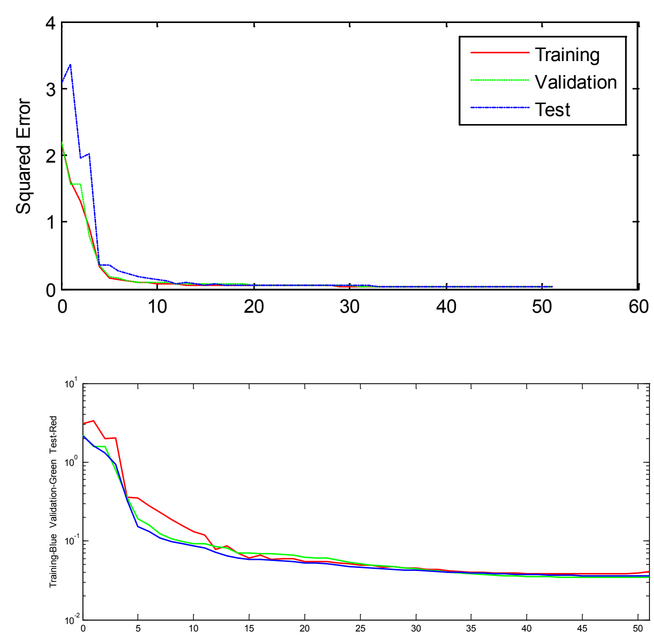

Fig. 5. Performance of the Neural network

E. Recall and Prediction Accuracy

The accuracy of the adopted NNs model was first checked by recalling the same data initially use to train it (set 1). Once the model was deemed acceptable, its prediction accuracy was tested against a new generated set of data (set 2). It should be stressed that all of the data in this latter set were initially withheld from the neural networks. In a similar fashion as in the recall test, the input values from these sets of data were presented to the model to perform the necessary calculations and produce corresponding outputs. Figs. 6 to 8 respectively show a comparison between the theoretical SAP2000 results and the recalled values by the ANN models.

For the models adopted in this work, the prediction accuracy is investigated. Data (Set 2) which consist of 50 randomly selected combinations is used to perform three ANN prediction tests. As mentioned earlier, all of the data in this testing set was initially withheld from the ANN. The results of these tests are shown in Figures 9 to 11. The closeness of the points to the equality line serves only to indicate the validity of the ANN models.

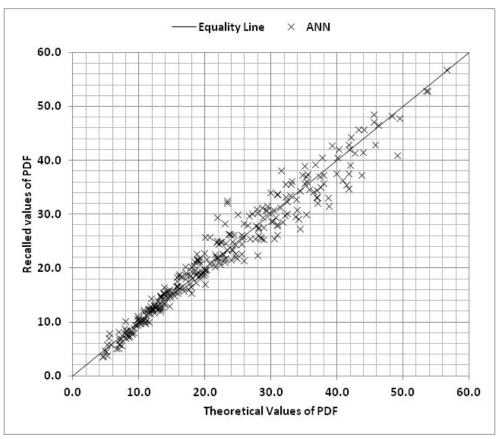

Fig. 6. Recalled PDF values by ANN vs. theoretical data (set1)

IV. SUMMARY AND CONCLUSION

The feasibility of using ANN to model and predict the dynamic behavior of Seismic-Isolated (SI) systems was investigated. THA was performed using SAP2000 for three MDOF systems representing a typical seismic isolated structure with a natural period of vibration equal to 2.5 s. Two ensembles of seven ground motion records representing two hazard levels (DBE and MCE) and return periods (475 and 950 years) were used.

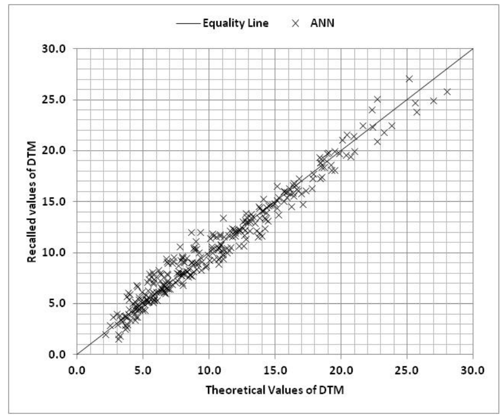

Fig. 7. Recalled DTM values by ANN vs. theoretical data (set1)

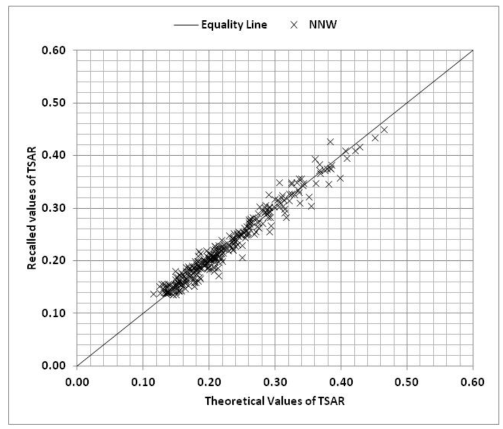

Fig. 8. Recalled TSAR values by ANN vs. theoretical data (set1)

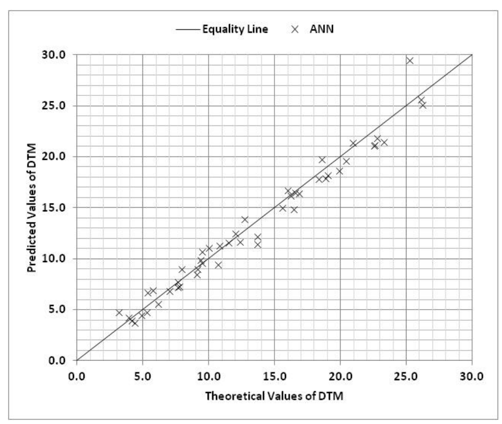

Fig. 9. Predicted PDF values by ANN vs. theoretical data (set2)

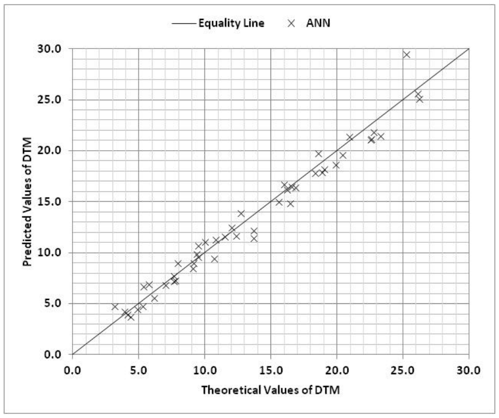

Fig. 10. Predicted DTM values by ANN vs. theoretical data (set2)

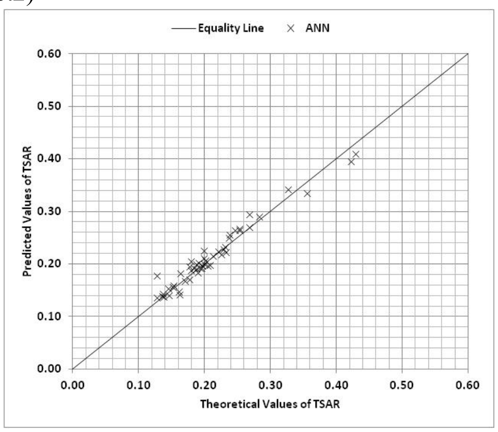

Fig. 11. Predicted TSAR values by ANN vs. theoretical data (set2)

The range of the SI system properties covered several feasible solutions comparable to the state-of-the-practice designs. Three key response parameters were selected to be modeled using MRA, namely; DTM, PDF, and TSAR of the isolated structure compared to the fixed-base structure. The response parameters, as well as the characteristics of the ground motions were utilized to develop several ANN models. For each of the key response parameters, the best fitting ANN models were selected. The design process of SI systems is iterative, complex and requires considering many feasible alternatives. Moreover, the most widely used analysis tool, the nonlinear THA, is very expensive in terms of CPU time which adds another layer of complexity to the situation. Therefore, simplifying techniques are extremely valuable especially at the preliminary design stages. In this investigation, it was demonstrated that the ANN modeling is a strong candidate to accompany, if not replace, the nonlinear THA. Once ANN models are developed through performing rigorous nonlinear THA, such as the presented work, several design options of SI systems can be easily selected and compared. Since the use of ANN models to evaluate the key response parameters is significantly simpler than performing THA, much more feasible solutions can be readily investigated and compared. This can be particularly valuable in the early design stages of SI systems utilizing the NRB-VFD combination.

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