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# A comparative study between the ANN-based and the current methods for seismic response estimation in the case of single degree of freedom systems

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***Abstract*** – The target displacement is one of the most critical performance indicators in the seismic vulnerability assessment. The Nonlinear Time History Analysis (NL-THA) is the most reliable method for calculating the seismic response of any building by solving the differential equation of motion. However, this procedure is considered time-consuming, and it needs expertise to perform. For that reason, many codes and standards have proposed and adopted various methods and procedures to estimate and predict the seismic response and target displacement. These alternative methods represent some prediction uncertainties.

Machine Learning (ML) algorithms became an exciting tool in earthquake engineering due to their performance and prediction simplicity. This paper compares the target displacement prediction of a novel Artificial Neural Networks (ANNs) method to the Displacement coefficient Method (DCM) adopted by FEMA-356, the Modified Coefficient Method (MCM) adopted by FEMA-440, and the NL-THA. The comparison is performed to 10 Single degrees of Freedom (SDOF) with different vibration periods and yielding forces (fy). The ANN model uses the SDOF characteristics and the ground motion (GM) parameters to estimate the maximum inelastic response. The results show a high performance of the ANN-based method in terms of Mean squared Errors (MSE), Mean Relative Error (MRE), and Mean Absolute Error (MAE).

*Keywords – Machine Learning, Artificial Neural Networks, Target Displacement, Seismic Response Prediction, Artificial Ground Motions.*

## I. Introduction

The seismic response is one of the most important indicators in performance evaluation and vulnerability assessment of existing buildings [1] . Many procedures and approaches have been proposed to estimate the seismic demand and response [2] [3] [4] . ATC-40 [5] and FEMA [6], [7] proposed alternative procedures based on the capacity evaluation of the structures to calculate the performance point and the target displacement. All the proposed procedures used the Nonlinear Static Analysis (NSA) to evaluate the building's capacity and obtain the force/displacement relationship as a pushover curve. Due to some estimation uncertainties in the Capacity Spectrum Method (CSM), Displacement Coefficient Method (DCM), FEMA-440 proposed improved procedures (the Equivalent Linearization (EL) and the Modified Coefficient Method (MCM). The DCM and the

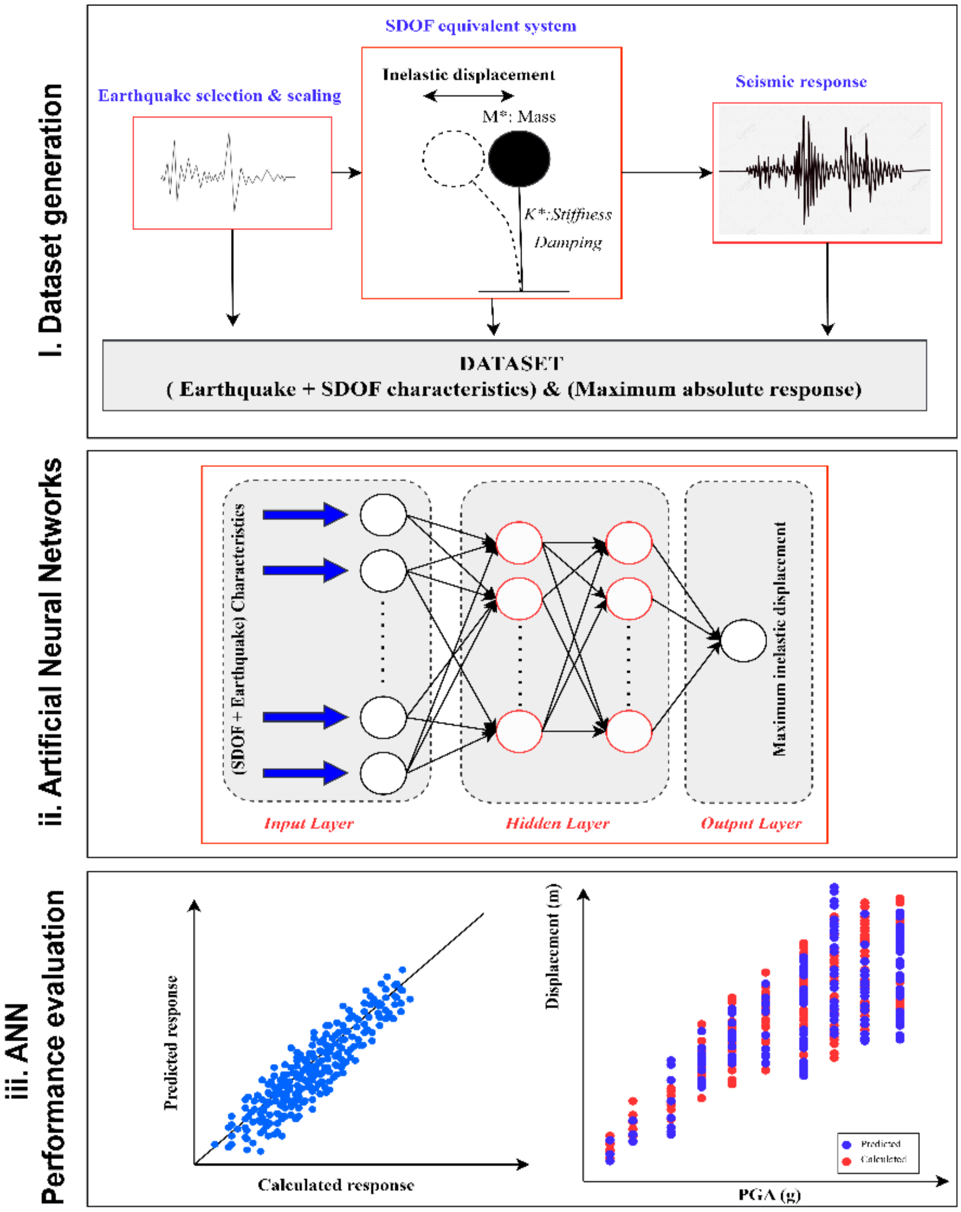


Figure 1 The used ANN method for the target dispalcement prediction

MCM showed a better estimation of the target displacement than the CSM and the EL for a various vibration period.

In the last decade, Artificial intelligence become a helpful tool that can be used in many fields with remarkable performance using Machine Learning (ML) techniques. One of these techniques we have the Artificial Neural Network (ANN). The ANN is a supervised ML that can find the relationship between the inputs and the outputs after the training and testing phases. These techniques showed a good performance in earthquake engineering [8] [9] [10]. It reduces processing time, simplifies prediction, and avoids human intervention. Therefore, an ANN model is proposed to predict the seismic response of an equivalent SDOF system subjected to Artificial Ground Motions (AGMs). The performance of the ANN model will be compared to the FEMA procedures results (DCM and MCM) in terms of predictability, Mean Squared Errors (MSE), Mean Relative Error (MRE), and Mean Absolute Error (MAE). The study will be applied to 10 SDOF systems with various vibration periods (0.1 sec – 3 sec) and with four different yielding forces (fy) (100 N, 400 N, 700 N, and 1000 N).The displacement coefficient method (FEMA-356)

In some cases, the NSP is selected to estimate the seismic response of a building. It is used to calculate the structural capacity and to predict the performance during an earthquake event. The target displacement represents the maximum response likely when the building is subjected to a ground motion. FEMA-356 proposes a simplified formula to calculate the target response using some coefficients $C_i$ as shown in equation (1).

$$\boldsymbol{\delta_T = C_0 C_1 C_2 C_3 S_a \frac{T^2}{4\pi^2} g} \quad (1)$$

Where:

- C0: is a modification factor to relate the SDOF 's spectral displacement to the MDOF's response.
- C1: is a modification factor that relates the inelastic expected response to the elastic response.
- C2: is a modification factor that represents the effect of strength and stiffness degradation on the maximum response.
- C3: is a modification factor that represents the effect of P-delta effect on the maximum response.
- Sa: is the spectral acceleration of effective fundamental period of vibration.
- T: is the effective fundamental vibration of the building.

## II. THE MODIFIED COEFFICIENT METHOD (FEMA-440)

FEMA-440 recommended several improvements to the coefficient method. It recommended changing to C1 and C2 equations, which will be based on empirical data, and C3 was eliminated from the equation (1).

C1 was modified to convert the maximum elastic displacement to an estimate for inelastic systems. C2 was also modified and recommended to be used only for structures that represent a significant strength and/or stiffness degradation behavior. C3 was eliminated for strength limit favor.

## III. THE ARTIFICIAL NEURAL NETWORK PREDICTION

The proposed method is an ANN model that uses the material characteristics of an SDOF and the earthquake parameters to estimate the maximum inelastic response of an SDOF system, as shown in Figure 1. The model is trained to 96,000 SDOF systems and 80 Artificial ground motions. OpenSees software generated the required dataset to train the ANN model. A Backpropagation algorithm was used, and the "Adam" algorithm was selected as an optimization technique. As shown in [11], the method showed remarkable accuracy and simplicity in estimating the MIRs. It can be seen when comparing the generated IDA curves, the median IDA curve, and the fragility curves using 30 unseen AGMs.

## IV. A COMPARISON STUDIES.

This study compares target displacement estimation using FEMA's and ANN-based methods. The results will be compared to the exact solution of the SDOF system using the NL-THA.

10 SDOF systems with various periods are selected to perform the NL-THA under 40 AGMs. The SDOFs will have various vibration frequencies (0.1 seconds to 3 sec). The yielding limit force will also be changed (100 N, 400 N, 700 N, and 1000 N). The SDOF systems will be subjected to scaled AGMs PGA=0.3 g. The mean displacement of each vibration period will be recorded using the ANN, the DCM (FEMA 356 and FEMA 440), and the NL-THA.

To evaluate the performance of the ANN and the accuracy of the method to the NL-THA results. Three statistical criteria are selected and summarized in Table 1.

The MRE, MSE, and MAE will be used to check the performance of each method for estimating the target displacement compared to the NL-THA results.

Equation (2), Equation (3), and Equation (4) are used formulas to calculate the MRE, MSE, and MAE, respectively.

$$MRE\ (\%) = \frac{\delta_{NLTHA} - \delta_{estimated}}{\delta_{NLTHA}} \times 100 \quad (2)$$

$$MSE = \frac{1}{N} \sum (\delta_{NLTHA} - \delta_{estimated})^2 \quad (3)$$

$$MAE = \frac{1}{N} \sum |\delta_{NLTHA} - \delta_{estimated}| \quad (4)$$

Where :

- $\delta_{NLTHA}$: is the maximum inelastic displacement using the NL-THA.
- $\delta_{estimated}$: is the target displacement using the DCM, MCM and the ANN.
- $N$: is the number of the calculated points.

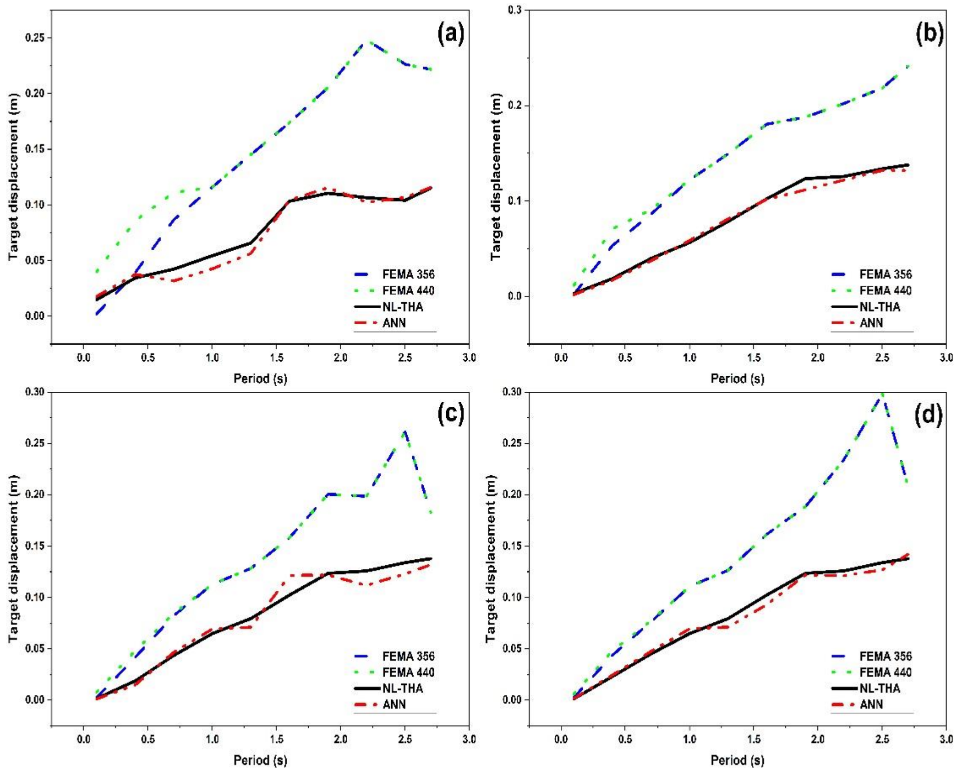


Figure 2 The mean target response of 10 SDOF systems with different yielding forces: a) fy=100 N, b) fy= 400 N, c) fy=700 N and d) fy=1000 N.

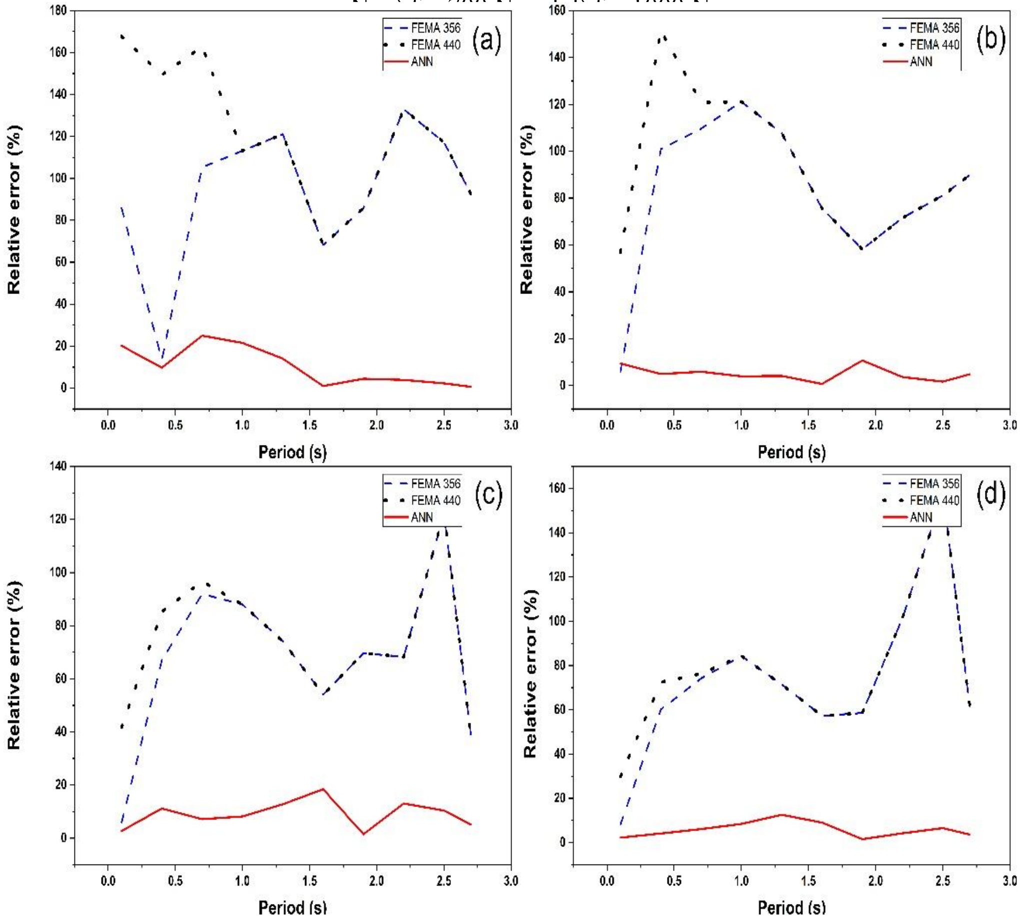


Figure 3 The MRE of 10 SDOF systems with different yielding forces: a) fy=100 N, b) fy= 400 N, c) fy=700 N and d) fy=1000 N.

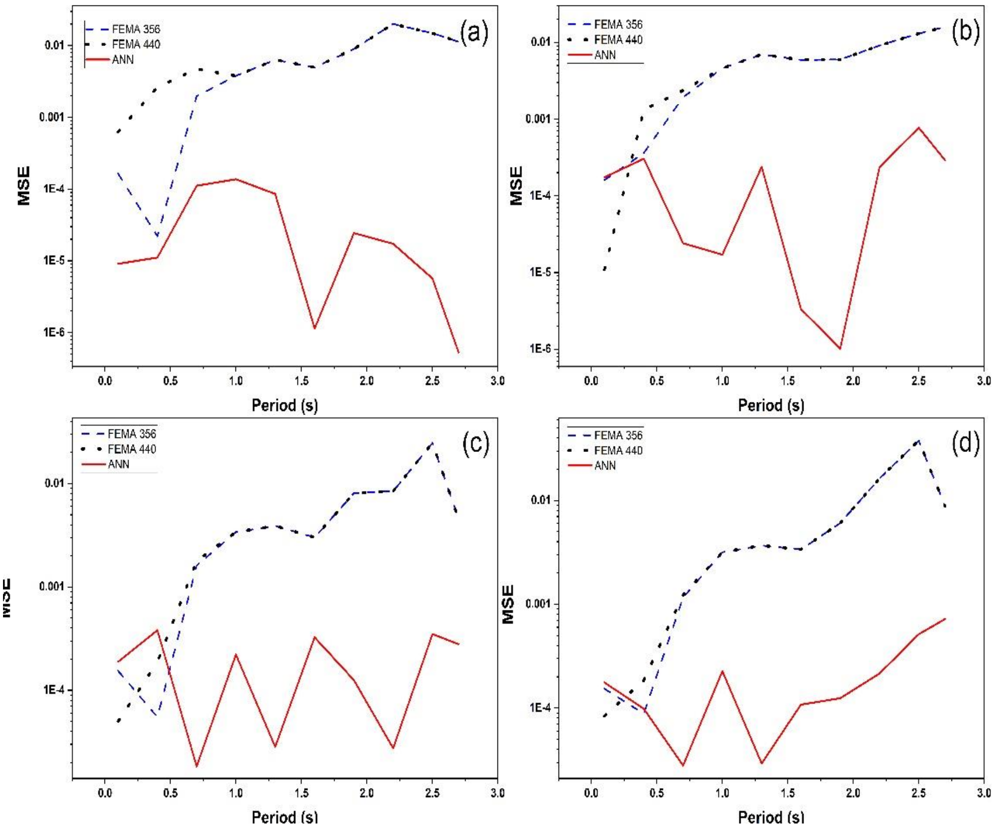


Figure 4 The MSE of 10 SDOF systems with different yielding forces: a) fy=100 N, b) fy= 400 N, c) fy=700 N and d) fy=1000 N.

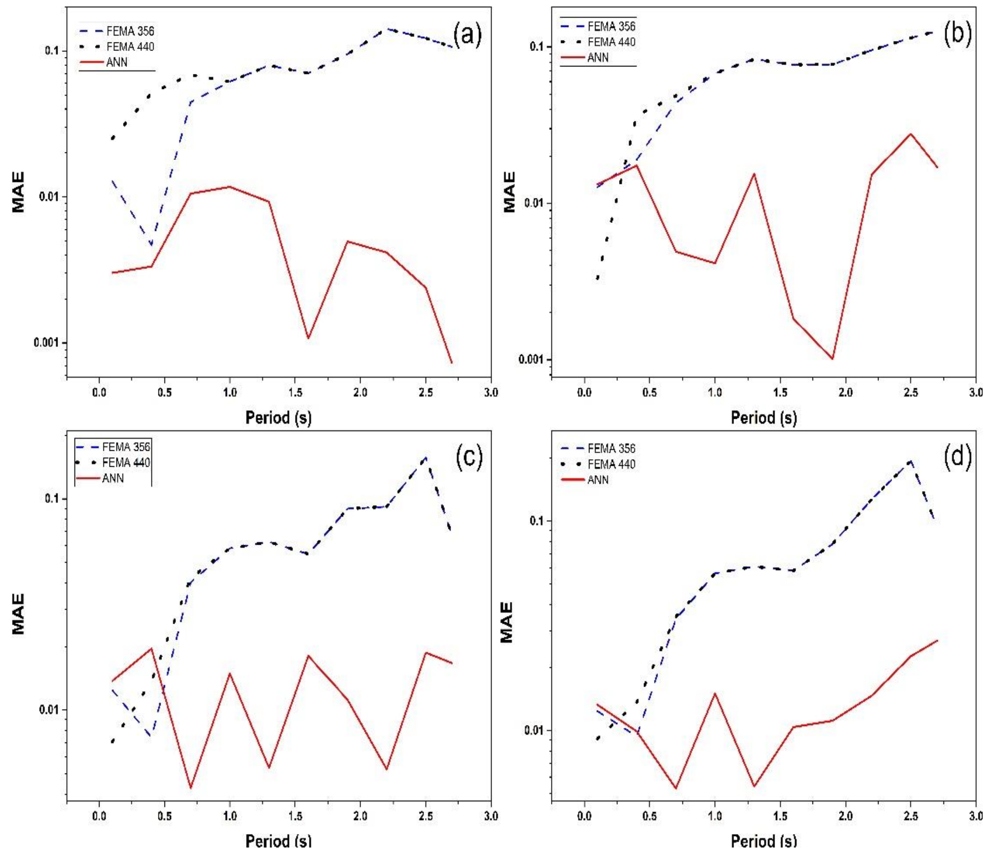


Figure 5 The MAE of 10 SDOF systems with different yielding forces: a) fy=100 N, b) fy= 400 N, c) fy=700 N and d) fy=1000 N.

## V. Results

The seismic response of the SDOF systems is calculated using four approaches. The DCM and the CM adopted in FEMA 356, FEMA 440, and the ANN model for the seismic response prediction are used in this work to be compared to the exact seismic response of the SDOFs using the NL-THA. The results represent a comparison of the seismic response in terms of maximum inelastic displacements (MInD), Mean Squared Error (MSE), Mean Relative Error (MRE), and Mean Absolute Error (MAE). Figure 2 (a- b- c and d) represent the mean MınD of all the SDOF systems subjected to 40 AGMs using the DCM, MCM, ANN, and the NL-THA for fy= [100, 400, 700, 1000] N, respectively. Figure 3, Figure 4, and Figure 5 illustrate the MRE, MSE, and MAE between the DCM, MCM, and ANN to the NL-THA.

## VI.Discussion

The DCM and the MCM adopted by FEMA 356 and FEMA 440 are the most used method to estimate the target displacement. They are used by many structural software like ETABS and SAP2000 due to their simplicity. In addition, they are more accurate than the Capacity Spectrum Method proposed by FEMA 356 and the improved version (Equivalent Linearization) proposed by FEMA 440. However, these methods show some uncertainties compared to the NL-THA results. Therefore, an ANN model is proposed to be used as an alternative to these methods without losing the accuracy of the seismic response prediction.

Figure 2 (a- b- c and d) showed remarkable predictability of the target displacement of the SDOF systems subjected to 40 AGMs. The methods' performance and accuracy of the methods are illustrated in Figure 3, Figure 4, and Figure 5.

As shown in Figure 3, the ANN method showed the lowest MRE for all the periods in the case of 100N, 400N, 700N, and 1000N. 20% is the highest MRE for the ANN prediction, exceeding 160% for the MCM and 150% for the DCM.

According to Figure 4, the ANN also showed the lowed MSE with a maximum error that did not exceed 0.0006 for SDOF systems that their period of vibration is higher than 0.5s in the case of Fy=[400,700,1000] N.

On the other hand, the DCM and the MCM showed a good performance for periods less than 0.5s ( MSE<0.0001) and the highest MSE for the other periods (MSE>0.01).

Based on Figure 5, which represents the MAE, the ANN showed the lowed MAE for all the studied range of periods in the case of fy=100N. On the other hand, the DCM and the MCM showed better estimations in the case of a period less than 0.5s. The ANN model predicts more accuracy for the rest of the period range (MAE < 0.025).

In light of the previous results, the ANN model illustrated that the proposed method could accurately estimate and predict the seismic response (the maximum inelastic displacement). Also, this technique was compared to the most known and used methods proposed by FEMA and showed better performance. The aim advantage of the proposed ANN method is the simplicity of performing it without the need for any programming skills. It can be used as an application that only requires the SDOF characteristics and the GM parameters.

## VII. Conclusion

The proposed ANN model showed remarkable prediction accuracy and performance compared to two existing FEMA methods (DCM and MCM). The method transforms the pushover curve into a bilinear capacity curve. The proprieties of the equivalent SDOF system and the GM parameters are used to predict the target displacement. This model is trained on 96,000 SDOF systems and 80 AGMs matched to a target response spectrum. This study aimed to compare the seismic response of the SDOF using the existing methods adopted by FEMA (DCM and MCM) and the ANN. The study is conducted on 10 SDOF systems with different vibration frequencies. 40 AGMs are used to calculate the mean response of each SDOF system. The results showed the high performance of the ANN in terms of MRE, MSE, and MAE. However, the DCM and the MCM showed a better accuracy of the SDOF systems with a period of vibration of less than 0.5 sec. These results proved that the ANN could also be used as an alternative method to the NL-THA to avoid complexity and processing time without losing the accuracy of the estimation.

In conclusion, artificial intelligence became an exciting tool for earthquake engineering to reduce the time and complexity of some analytical models. It can be trained on some experiences and scenarios and conclude their relationship. This process can be used to predict unseen cases, which may provide quick and accurate predictions without any complexity.

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