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Effective vibrating barriers design for the Zoser pyramid using artificial neural network

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ABSTRACT

Vibrating Barrier (ViBa) is a non-invasive strategy used to protect buildings, especially ancient and historic structures, from seismic wave vibrations. The ViBa is a spring-mass device installed at a separate location beneath the ground surrounding the structure in concern, for the purpose of reducing ground motion energy, without any intervention with the structure itself. The step pyramid of Zoser was one of the archeological monuments affected by the 1992 Earthquake in Egypt. In this work, a new approach of ViBa design is proposed to protect the step pyramid of Zoser using Artificial Neural Network (ANN). A numerical model was developed to test the predicted pyramid seismic behavior using the ANN-derived ViBa parameters. The ANN optimization approach shows a reduction in the peak step pyramid acceleration by 46 %. This reduction was obtained using tuning and optimization of the developed ANN.

1. Introduction

Traditional earthquake hazard mitigation systems are strengthening or using control systems. Structural strengthening is considered via taking advantage of advanced structural engineering techniques and smart materials which may lead to energy-dissipative system [1]. Control systems can be introduced as passive, active or semi active control systems. Seismic isolation system is a form of passive control system as it absorbs a significant amount of seismic energy. Active control system involves real-time monitoring of external excitations hence electrohydraulic actuators could be used to adjust the structural response. Semi-active control systems combine both techniques by using passive control systems with special materials with mechanical properties that can be modified over time based on the feedback from the monitoring systems [2–4].

The step pyramid of Zoser in Egypt is an important archeological site that reflects crucial stages in the Egyptian civilization development. Earthquakes represent a major hazard to such an important monument, and protection can be done in different forms such as strengthening [5] or using control systems [6]. However, these ways will require interventions that compromise the aesthetics and the historic value of the historic monument. Moreover, it is prohibited to change or modify such an important monument due to its cultural heritage. In this regard, a non-invasive strategy shall be adopted to decrease the vibrations on the step pyramid subjected to ground motions. The Vibrating Barrier (ViBa) [7–13] has been proposed recently as a device installed in the surroundings of the building under study to absorb a significant amount of the dynamic energy caused by ground motion. ViBa design in different applications and efficiency has been carried out through several studies. The use of ViBa to mitigate the seismic risk of nuclear reactors has been investigated by Cacciola and Tombari [7]. The effect of ViBa on piled structures has been demonstrated by Cacciola et al. [8]. Sensitivity analysis of the stochastic response of structures coupled with ViBa has been presented by Tombari et al. [9]. Vibration control of an existing building and a cluster of buildings through the vibrating barrier has been studied by Cacciola et al. [10] and Tombari et al. [11]. The Effect of equipping inerter with ViBa to reduce the mass required in the ViBa design has been suggested and investigated by Cacciola et al. [12]. Cacciola et al. [13] studied the use of ViBa in mitigating the seismic risk on the step pyramid by optimizing ViBa parameters using a stochastic approach, reducing the peak acceleration by 30 %. The stochastic approach uses a reduced-order ViBa-Soil-Pyramid model governing equations. The optimization problem is written as minimization of an objective function which can be solved with standard iterative algorithms for constrained optimization, such as the derivative-free method.

Artificial neural networks (ANN) in structural engineering and the

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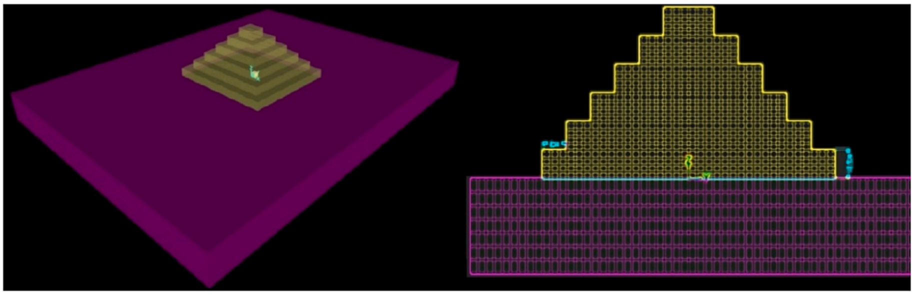
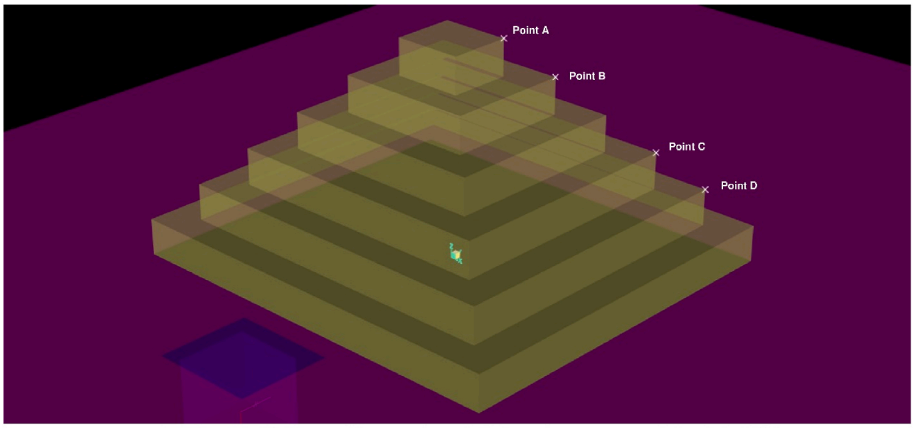
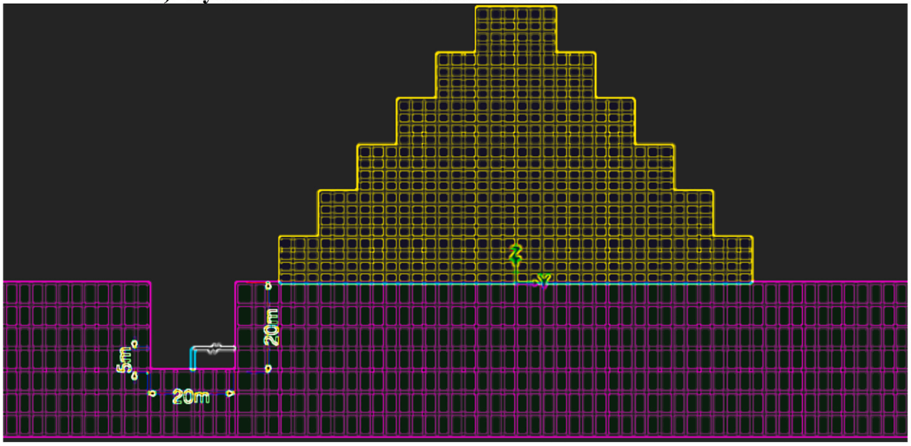


Fig. 1. Step pyramid 3D finite element model without ViBa.



a) Pyramid three-dimensional finite element model with ViBa.



b) Pyramid cross section with ViBa.

Fig. 2. Three-dimensional finite element model with ViBa and its cross sectional.

Table 1
Material properties for considered soil and the pyramid.

Soil			Pyramid		
Density (kg/ m^3)	E_s (kPa)	Poisson ratio	Density (kg/ m^3)	E_s (kPa)	Poisson ratio
2200	45 × 10^6	0.25	2900	45 × 10^6	0.25

Table 2
The results of the generated numerical model vs previous results [13].

	The generated Model	Reference [13]
Time Period	10.44 Hz	10.54 Hz
Peak Acceleration (No ViBa)	13.2 m/s^2	12.71 m/s^2
Peak Acceleration (with ViBa)	9.68 m/s^2	9.34 m/s^2

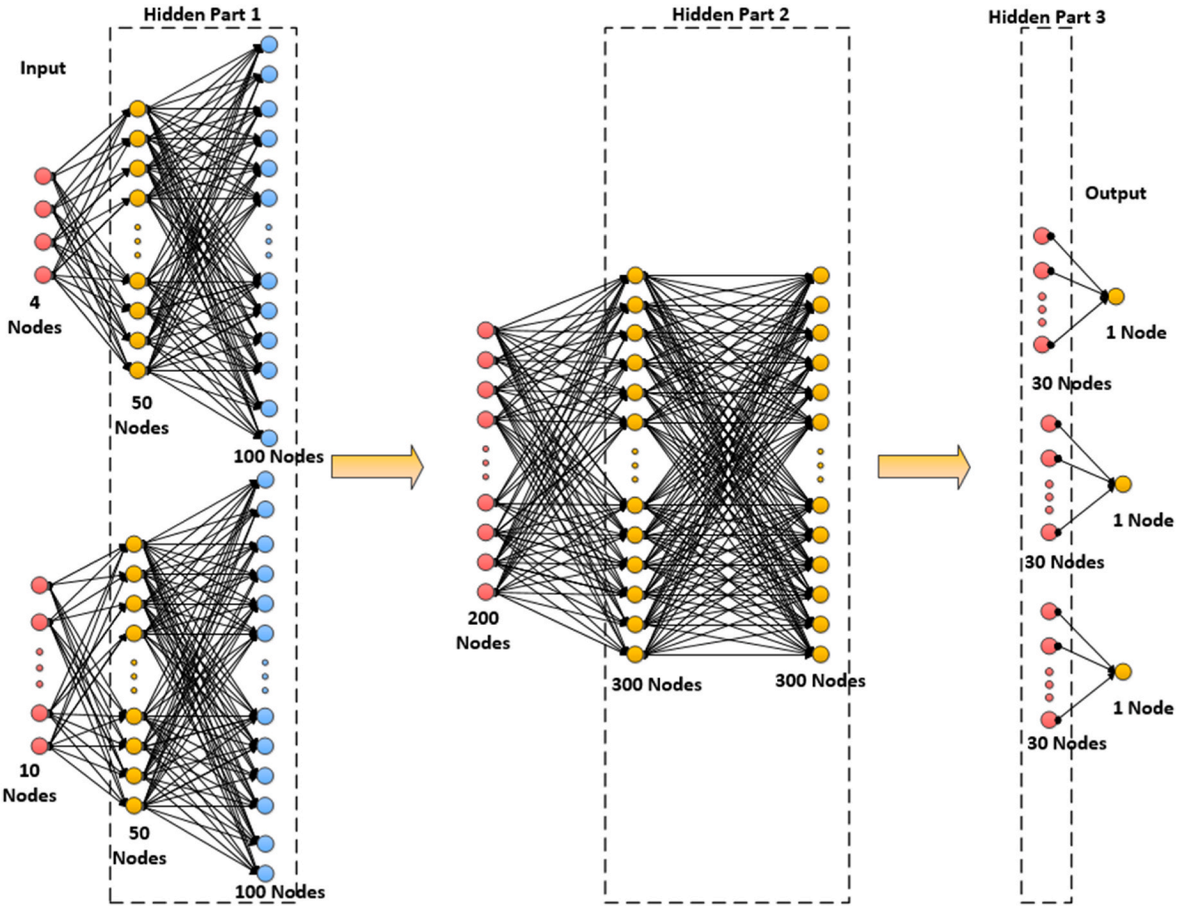


Fig. 3. The developed ANN configuration.

machine learning applications has been studied by Huu-Tai Thai [14]. A wide range of machine learning applications applied to structural analysis and design has been reviewed in Ref. [14]. Among these applications are structural health monitoring, fire resistance structures, resistance of structural members under various actions, and mix design of concrete. Huu-Tai Thai [14] discussed the challenges and future recommendations of ANN applications as well.

In this paper, ANN is used to optimize the Viba parameters as a new approach for Viba design as an alternative to the standard stochastic approach previously presented in Ref. [9]. The overall performance of the step pyramid will be investigated concerning the optimized Viba parameters, specifically the reductions in peak pyramid acceleration, and the results are compared to those of the traditional stochastic approach.

2. Problem statement

The Zoser step pyramid is one of the important archeological monuments that were affected by the well-known 1992 earthquake in Egypt. Therefore, an unconventional earthquake mitigation system must be presented. The use of ViBa to protect these monuments is one of the most suitable approaches. The optimization of ViBa design was previously involved using a multi-step and stochastic approach as presented in Ref. [9]. However, as proposed in this paper, the use of ANN can be employed to optimize the design process and introduce several ViBa designs. The optimization of ViBa is performed by studying the effect of its distance from the step pyramid, mass, and stiffness on the response of the pyramid.

Data generation is a crucial step in developing a suitable ANN. To capture the effect of each parameter, several numerical data sets have to be created, in which one parameter is varied at a time. A three-dimensional finite element model is developed as shown in Figs. 1 and 2. Each parameter data are varied as follows.

- ViBa distance is varied from 10 to 30 m from the pyramid base.
- ViBa mass ranges from 10 % to 100 % of the pyramid total mass.
- ViBa stiffness is assumed to cover frequency range between 0.1 and 15 Hz.

The pyramid has a rectangular base of dimensions: 108 × 120 m. The pyramid's height is 63 m [13]. The material properties of the pyramid are presented in Table 1. The bedrock is modeled as presented in the aforementioned study [13], which is located at depth of 35 m.

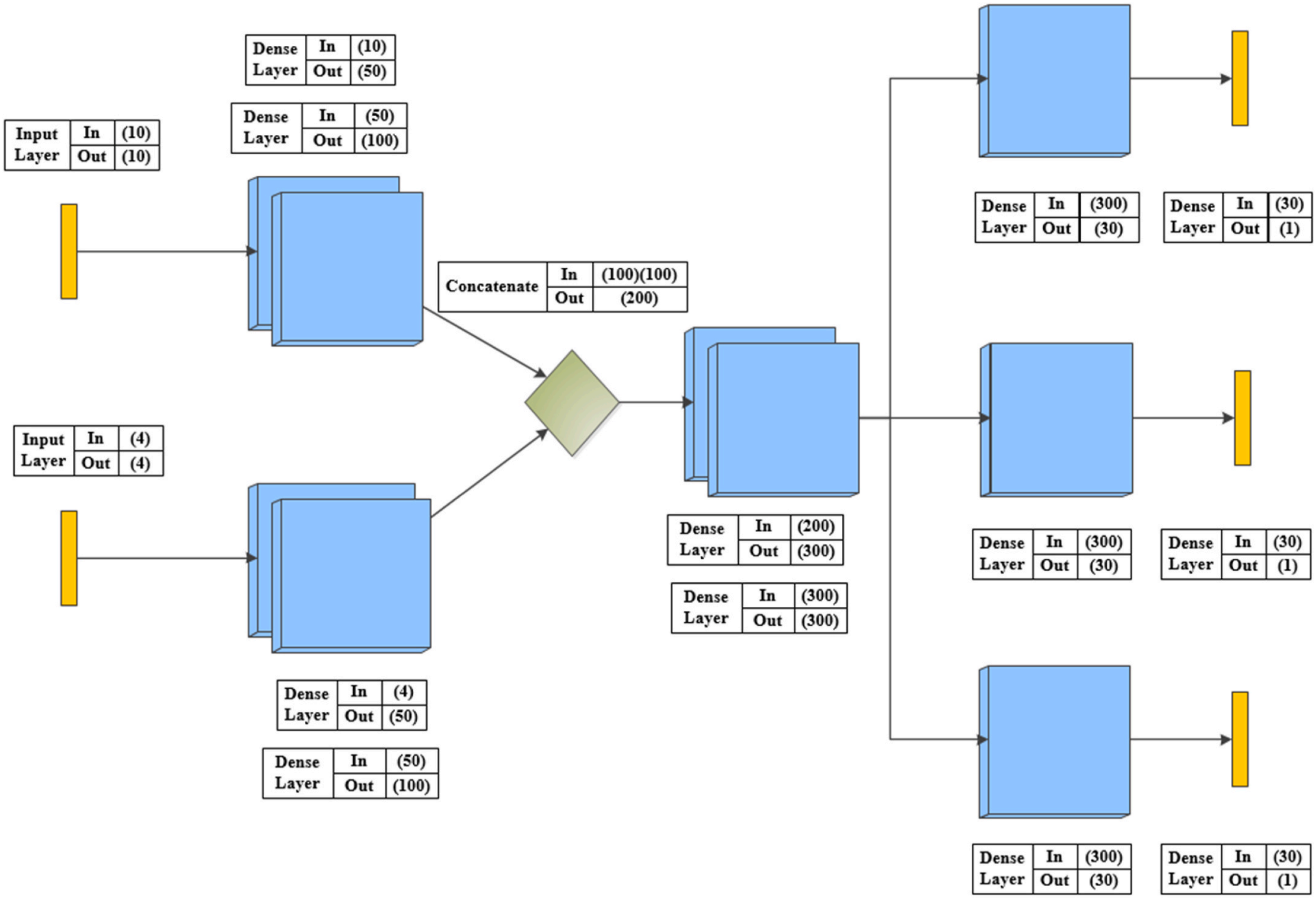


Fig. 4. The developed ANN structure.

3. Numerical model verification

In order to verify the used numerical model, the obtained results are compared to those obtained from the previous study in Ref. [13]. In this study, ViBa is located at distance of 15 m away from the pyramid base. The ViBa mass is 80 % of the pyramid total weight, and the considered ViBa stiffness is 7190.6 GN/m. The results are demonstrated in Table 2. It can be seen that the difference is less than 5 %. Therefore, this numerical model is used further to generate the training data set for the considered ANN.

4. The developed ANN

A sequential neural network is used which has two branches input layer. One branch is for the acceleration, and another is for response values. Three branches are used for the output layer for each of the three ViBa parameters (ViBa mass (mViBa), ViBa stiffness (K), and its distance from the pyramid (d)). The hidden layers are used in three segments. The middle segment is the collective body. Fig. 3 demonstrates the configuration of the developed network.

The ANN configuration consists of one input layer that has 10 + 4 nodes. The 10 nodes are the highest ten acceleration peaks in the earthquake record. Another 4 nodes are the four desired points, which are chosen to measure the pyramid response (Recall Fig. 2: points A, B, C, and D). The developed ANN has three output nodes. The three output nodes are: the ViBa mass (mViBa), ViBa stiffness (K), and its distance from the pyramid (d). As shown in Fig. 3, the 6 hidden layers used have the following nodes (50, 50, 100, 100, 200, 300, 300, 30, 30, 30). These number of neurons are obtained using optimizer. The “tanh” activation function is used. Fig. 4 demonstrates the structure of the developed network.

A subroutine is coded using Visual Basic for Applications (VBA) inside MS-Excel to automate the generation and to accelerate the large training dataset. The flow chart of the subroutine is demonstrated in Fig. 5. The flowchart starts with browsing the spreadsheet location that contains all selected ViBa masses. A separate spreadsheet tab is created for each mass. Hence, a loop on the masses is executed. Then a mass value and a single stiffness value are applied to the FE model. After executing the 3D FE model, the obtained maximum and minimum displacement results are saved in the same mass spreadsheet.

In this work two earthquake records are used. The first record is denoted by (EG SPEC). It is an artificial record generated from the

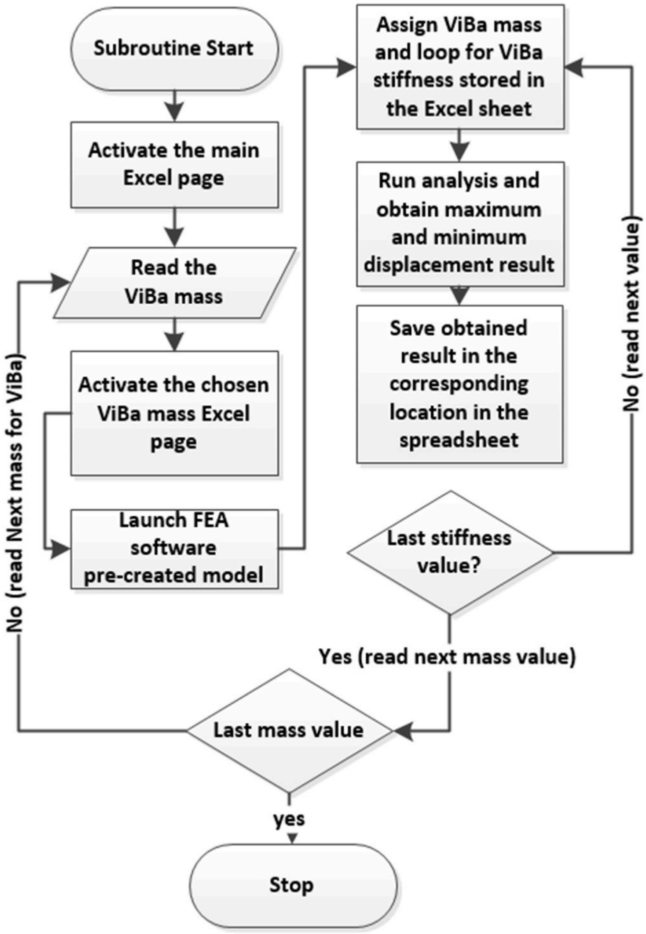


Fig. 5. Flowchart of data generation code.

response spectrum in the Egyptian code of practice [15]. The second one is the well-known 1992 Cairo earthquake. A total of 6300 training cases (data set) was generated using the EG SPEC. The model was trained using random 10 %, 30 %, 50 %, 90 % of the total data set. Hence, both learning curves and percentage error in test results for each training size are compared. The Learning curves demonstrated in Fig. 6 which shows that the most promising training size is 70 % with the lowest loss of 7.84 %. This is confirmed by the testing cases results, in which the training size of 70 % has the lowest error, that was about 4 %.

The output 3 parameters obtained from the ANN (m_{ViBa}, K, d) after training are applied to FEM 3D model to be tested using the 1992 Cairo earthquake. Table 3 demonstrates the obtained results.

The seismic response of the pyramid is computed using the 3D finite element model after applying the obtained designed ViBa parameters. Results demonstrate a reduction of 38 % in peak acceleration compared to the peak acceleration without ViBa as shown in Fig. 7.

5. ANN tuning

From the previously obtained results, the maximum reduction reached is 38 % (recall Table 3) compared to 30 % that was obtained in Ref. [9] using the stochastic approaches. In order to enhance the performance of the developed ANN, fine tuning is performed. The structure of this neural network is the same as before but instead of using a fixed number of iterations, the iterations are stopped when the loss calculated is below a certain value. This certain value is chosen to be 8 %.

In this case, the learning curves demonstrate that the most promising training size is 90 % with the lowest loss of 7.4 % as shown in Fig. 8. This is confirmed by testing results in which the training size of 90 % has the lowest error of 2 %. The parameters obtained from this network are then tested using the 3D finite element model, hence the results are demonstrated in Table 4.

From the results in Tables 4 and it can be seen that an improvement in acceleration reduction from 38 % to 44 % is gained. The top point of the pyramid response in this case is recorded as shown in Fig. 9. In an attempt for further enhancement of the performance of the developed ANN, CHAID algorithm [16] is used to determine the significance of each parameter in training data as shown in Fig. 10.

Hence, extra data with more variation in ViBa frequency are generated to enhance the performance of the developed ANN. The frequency range used is from 9 to 11 Hz which is around the natural frequency of the first mode of the pyramid (10.5 Hz) with a step of 0.1 Hz. The generated data is added to previous training sets (70 % and 90 %) and are fed into the developed ANN.

Fig. 11 demonstrates the learning curves that demonstrate the most promising training size is 90 % with the lowest loss of 7.2 %. The parameters obtained from this network are then tested using the 3D finite element model. The obtained results are presented in Table 5. A slight improvement in the performance of the ANN, increasing maximum reduction from 44 % to 46 %, is gained.

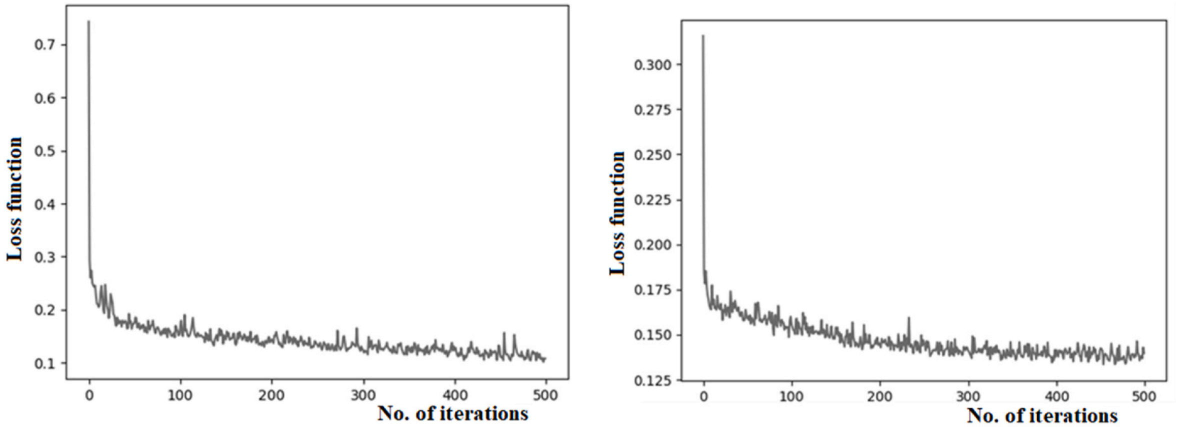
The top displacement of the pyramid response is computed from the finite element model and demonstrated a reduction in peak acceleration of 46 % as shown in Fig. 12.

6. Conclusions

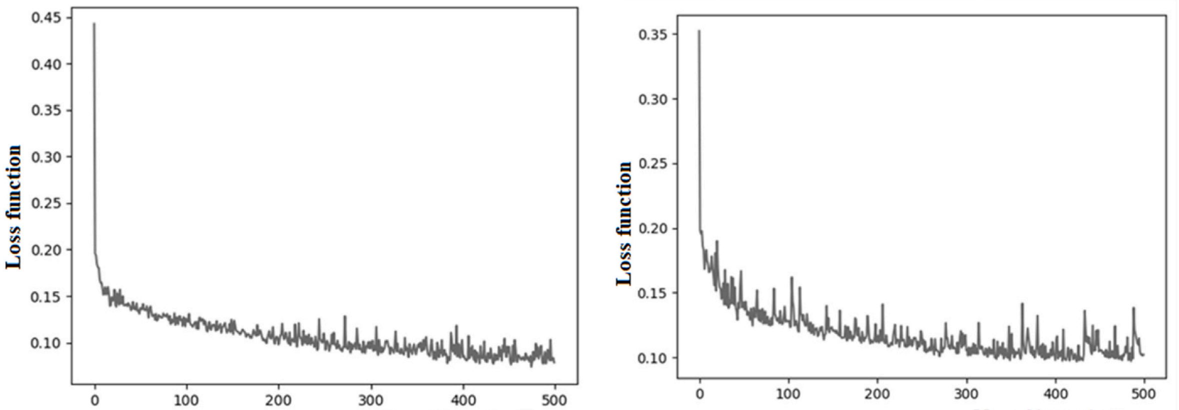
In this paper, innovative ViBa design methodology was presented using sequential ANN. This methodology was applied to the Zoser step pyramid in Egypt. A three-dimensional finite element model was considered to generate training data. The achieved reduction in the response of the top point in the pyramid was 46 %. Tuning and optimization processes were performed on the developed ANN to obtain this reduction. Further enhanced performance and other methods such as the use of other types of ANN, such as the recurrent neural networks can be tested as future work. The use of ANN in design and optimization of ViBa simplifies the design process which enables engineers to design more complicated patterns of multiple ViBas. The authors will investigate further ViBa design using this promising technique in future publications.

CRediT authorship contribution statement

Ahmed Fady Farid: Writing – original draft, Software, Investigation, Conceptualization. **Moataz A. Mabrouk:** Writing – original draft, Validation, Formal analysis, Data curation. **Youssef F. Rashed:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ashraf Ayoub:** Writing – review & editing, Supervision, Project administration, Funding acquisition.



a) 30% of data learning curve b) 50% of data learning curve



c) 70% of data learning curve d) 90% of data learning curve

Fig. 6. Learning curves for the used ANN.

Table 3
Results of the used ANN.

Training Size %	Target Red. %	Computed ViBa using EG SPEC			EG SPEC	EQ1992
		K	$m_{ViBa}/m_{Pyramid}$	d	Computed Red. %	Computed Red. %
30	10 %	3.92E+09	0.31	24.0	9 %	10 %
	30 %	8.40E+09	0.95	9.6	17 %	29 %
	50 %	4.99E+10	1.05	6.2	13 %	31 %
	70 %	4.01E+10	0.95	8.2	12 %	32 %
	90 %	4.79E+10	1.03	4.9	13 %	34 %
50	10 %	8.60E+08	0.35	7.8	10 %	5 %
	30 %	9.13E+09	0.84	14.2	10 %	33 %
	50 %	4.05E+10	0.92	12	13 %	35 %
	70 %	2.32E+10	0.95	11	12 %	36 %
	90 %	2.40E+10	0.94	11.2	12 %	36 %
70	10 %	6.43E+09	0.73	21.4	10 %	24 %
	30 %	1.49E+10	0.85	4.6	12 %	33 %
	50 %	1.97E+09	1.04	33.4	9 %	3 %
	70 %	2.38E+09	0.85	35.2	11 %	5 %
	90 %	2.90E+09	0.67	31.6	11 %	8 %
90	10 %	4.37E+09	0.52	11.2	11 %	33 %
	30 %	4.01E+10	1.06	14.1	11 %	38 %
	50 %	5.10E+10	1.00	13.1	12 %	35 %
	70 %	4.13E+10	0.92	13.2	13 %	35 %
	90 %	3.57E+10	0.84	13.4	13 %	31 %

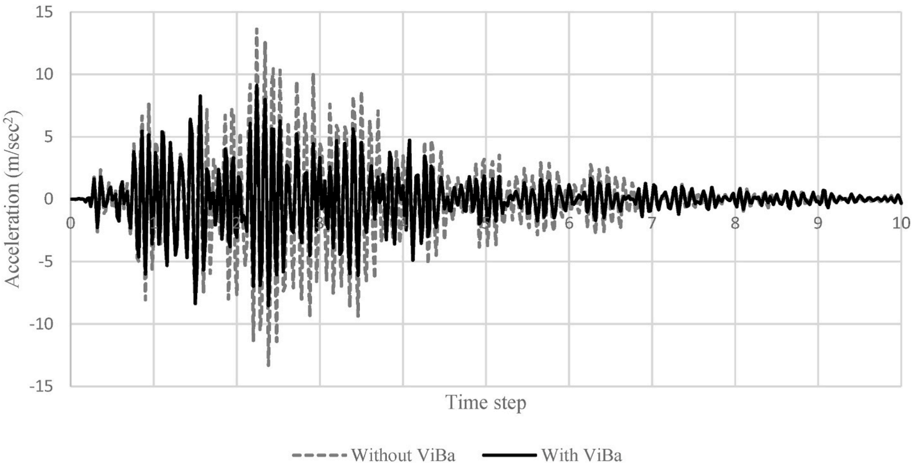


Fig. 7. Peak acceleration response for the top point of the step pyramid considering Cairo 1992 earthquake.

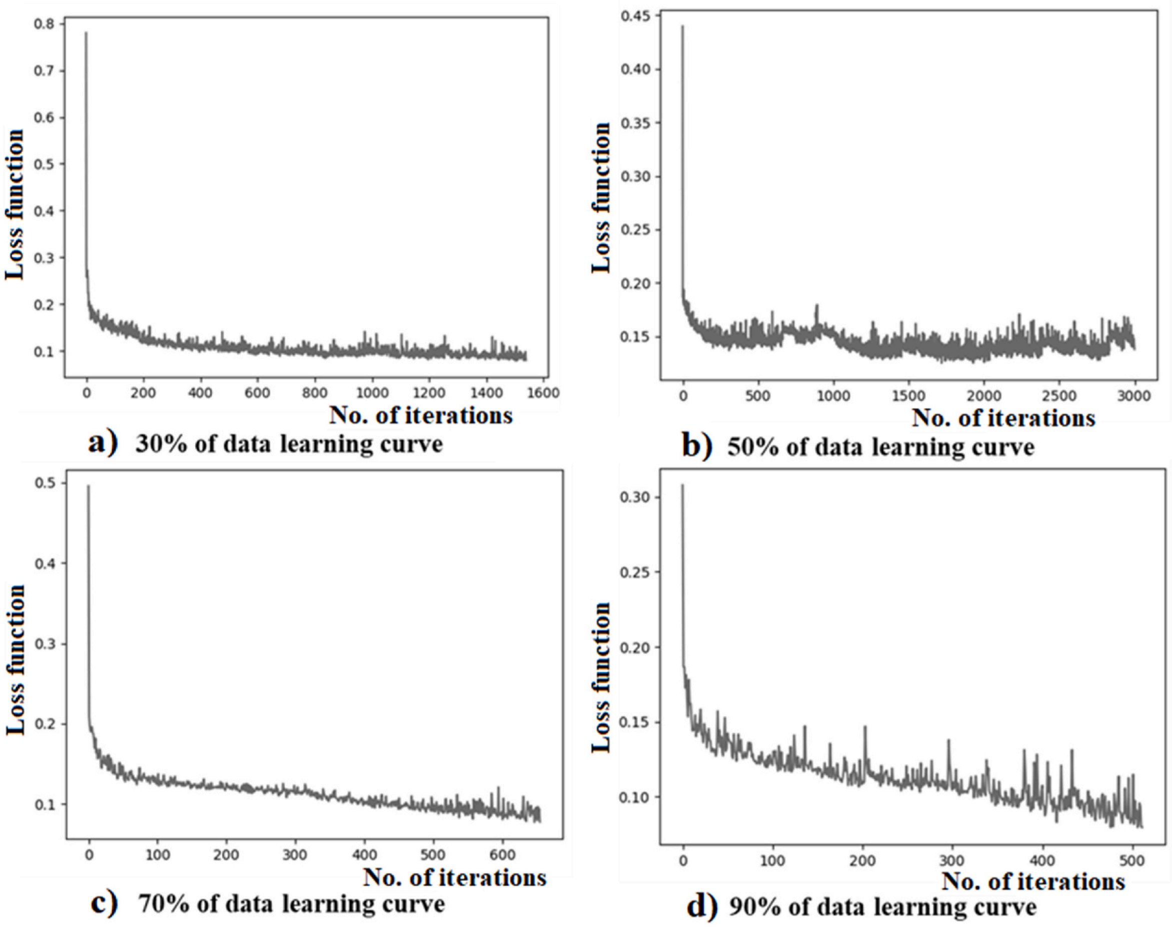


Fig. 8. Learning curves for the used ANN with optimized number of iterations.

Table 4
Results of the used ANN with optimized number of iterations.

Training Size %	Target Red. %	Computed ViBa using EG SPEC			EG SPEC	EQ1992
		k	$m_{ViBa}/m_{Pyramid}$	d	Computed Red. %	Computed Red. %
30	10 %	−1.27E+08	1.02	8.4	3 %	5 %
	30 %	1.16E+09	1.06	5.6	11 %	4 %
	50 %	6.03E+10	1.04	3.3	9 %	32 %
	70 %	5.96E+10	1.04	3.7	8 %	32 %
	90 %	6.21E+10	1.04	3.5	9 %	32 %
50	10 %	2.42E+09	0.29	13.8	6 %	4 %
	30 %	5.45E+10	0.84	11.9	10 %	21 %
	50 %	6.22E+10	0.84	11.9	10 %	21 %
	70 %	6.24E+10	0.85	14.1	13 %	23 %
	90 %	6.27E+10	0.85	16.7	10 %	20 %
70	10 %	1.21E+10	0.52	8.2	10 %	−3%
	30 %	1.45E+10	0.96	8.0	11 %	40 %
	50 %	4.18E+10	0.98	7.5	9 %	33 %
	70 %	6.38E+10	0.89	7.3	10 %	31 %
	90 %	5.61E+10	0.75	7.2	10 %	14 %
90	10 %	3.82E+09	0.40	2.6	8 %	14 %
	30 %	1.48E+10	1.06	19.0	11 %	25 %
	50 %	4.88E+10	1.19	0.0	16 %	40 %
	70 %	4.72E+10	1.22	6.6	15 %	44 %
	90 %	4.70E+10	1.22	7.8	15 %	43 %

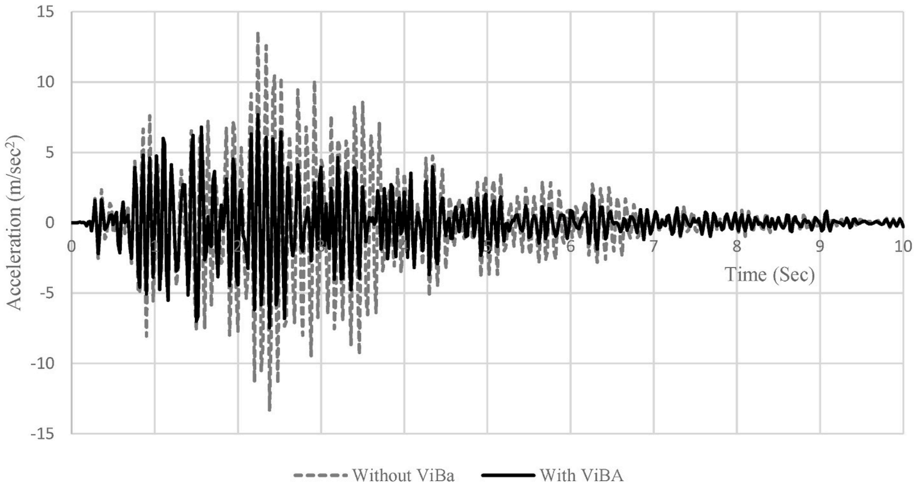


Fig. 9. Peak acceleration response for the top point of the step pyramid after ANN optimization in case of Cairo 1992 earthquake.

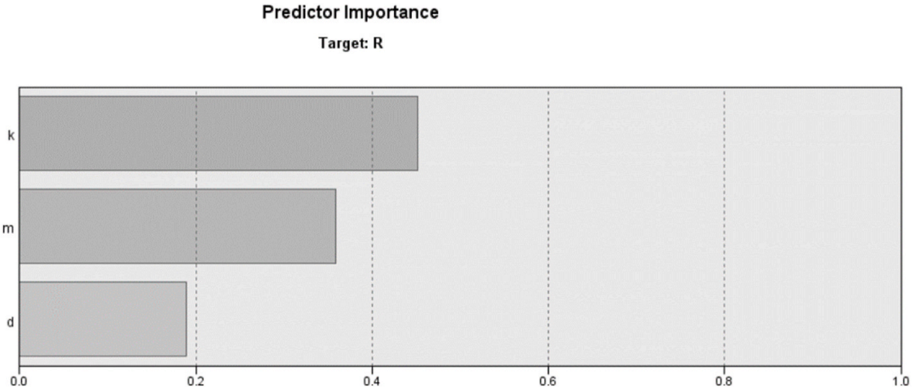
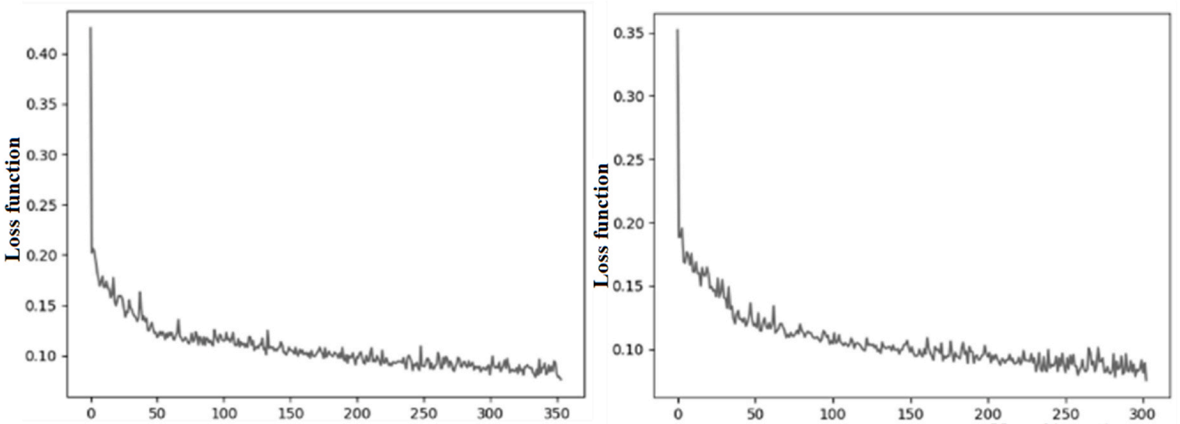


Fig. 10. Importance factor for ViBa parameters using the CHAID algorithm.



a) 70% of data learning curve **b)** 90% of data learning curve

Fig. 11. Learning curves for the used ANN with the CHAD algorithm data.

Table 5
Results of the used ANN with the CHAD algorithm data.

Training Size %	Target Red. %	Computed ViBa using EG SPEC			EG SPEC	EQ1992
		k	$m_{ViBa}/m_{Pyramid}$	d	Computed Red. %	Computed Red. %
70	10 %	2.17E+10	0.51	24.1	10 %	3 %
	30 %	3.2E+09	0.93	4.7	15 %	14 %
	50 %	8.07E+10	1.08	4.9	12 %	32 %
	70 %	5.77E+10	0.75	4.8	10 %	−8%
	90 %	4.36E+10	0.80	6.1	13 %	23 %
90	10 %	2.33E+10	0.55	26.7	12 %	9 %
	30 %	1E+10	0.78	8.3	12 %	37 %
	50 %	5.05E+10	0.99	4.0	9 %	31 %
	70 %	3.95E+10	1.20	2.2	16 %	46 %
	90 %	3.23E+10	1.29	4.7	20 %	43 %

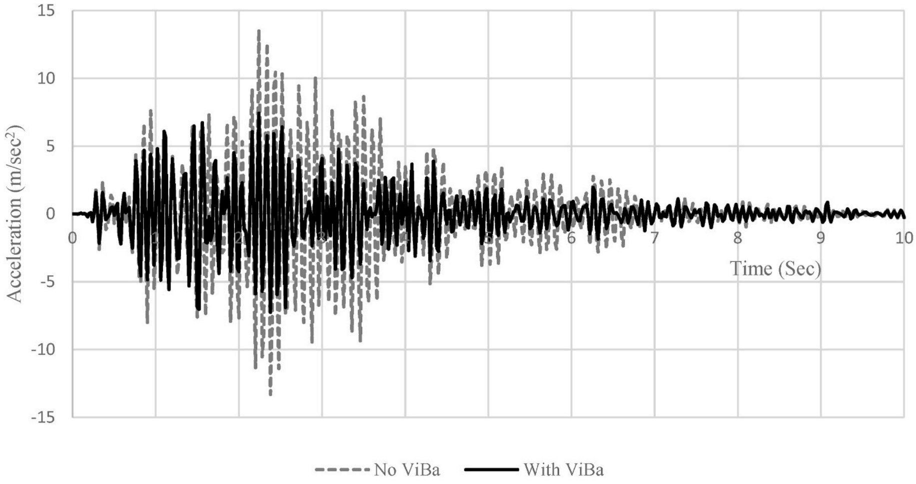


Fig. 12. Peak acceleration response for the top point of the step pyramid using the CHAD algorithm in case of Cairo 1992 earthquake.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ashraf Ayoub reports financial support was provided by Arts and Humanities Research Council. Youssef Rashed reports was provided by Science and Technology Development Fund. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

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