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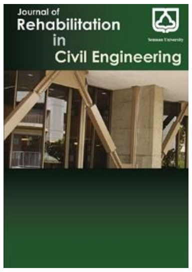

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A New Relationship to Determine Fundamental Natural Period of Vibration for Irregular Buildings in Height Using Artificial Neural Network

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ABSTRACT

One of the most important structural features is fundamental vibration period which depends significantly on the inherent characteristics of structures. Seismic codes and some researchers estimate experimentally and mathematically fundamental vibration period using the number of stories or the overall height of the building. The consequences of evaluating the various relationships have been resulted based on structural height, mass, stiffness and number of stories. As the overall height and the number of stories do not make difference between regular and irregular structures, so it seems that mass and stiffness of each story is so important in zone of building vibration period. Considering the importance of irregular buildings, a new relationship proposed to determine fundamental natural period of vibration for elastic regular and irregular buildings in height using artificial neural network. The accuracy of the proposed relationship is perfectly validated and confirmed by numerical calibrations and matrix analyses.

1. Introduction

The philosophy of fundamental building period is the time of a completed cycle for sweep movement of top level of building during earthquake. This parameter, which plays a key role in seismic analysis and design, is the inverse of the building frequency and depends on the intrinsic properties of building structure. In order to determine building vibration periods, different codes around the world have approximately suggested various equations based on the overall height of the building and the number of stories. In fact, fundamental period of vibration plays an important role in earthquake studies, since earthquake induced excessive displacement to the building system and consequently structural damage under the increment of the

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fundamental period of vibrations. Therefore, common special equation for single degree of freedom system is generally used based on mass and stiffness of the structure, which is defined as:

$$T = 2.\pi.\sqrt{\frac{m}{k}} \tag{1}$$

Where m is lumped mass and k denotes structural stiffness. For this purpose, a general equation based on overall height of the building was considered which is written as the below:

$$T = C_i.H^{\alpha} \tag{2}$$

T is building vibration period; *H* denotes the overall height of the building, *C* and α are the factors for various seismic resistant system in different codes. The value of *C* has been estimated to be 0.03 and 0.035 for reinforced concrete and steel buildings, respectively and α also suggested to be 0.75 for both buildings in *UBC* [1], *SEAOC* [2] and *NEHRP* [3]. On the other hand, *ATC3-06* [4] has been recommended the coefficient of *C*=0.025 for RC buildings, which is 0.05 and 0.016 in Iranian code of practice for seismic resistance design of buildings [5] and *ASCE/SEI 7-10* [6], with the α factor of 0.9, respectively. These codes present building vibration period based on the overall height of the building, so that the effect of structural mass and stiffness as well as material and building properties have not been considered. Using the number of stories, an empirical and alternative equation is also available to approximately determine building vibration period [7].

$$T = 0.1N \tag{3}$$

Where *N* is the number of stories. According to the structural system type, Goel and Chopra [8] presented an improved version of Equation (2), where *C* and α were typically suggested to be 0.053 and 0.75, to estimate the building vibration period to use in equivalent lateral force analysis. They have also evaluated the building period formulas for concrete shear wall buildings [9]. Furthermore, Hong and Hwang [10], Verderame et al. [11], Kwon and Kim [12] and Lee et al. [13] presented building vibration period based on structural system type. Considering infill walls, Ricci et al. [14] and Crowley and Pinho [15] investigated the fundamental vibration period of some buildings and evaluated the effectiveness of infill walls onthis parameter. A series of regular *RC* frame buildings were modeled using 3D finite element method and modal eigenvalue analysis was carried out considering the effects of infill walls by Amanat and Hoque [16]. In this study, it was shown that the models without infill walls give significantly longer period than the amount predicted by the code equations. The influence of soil flexibility on building vibration period was also examined by Stewart et al. [17], Avilés and Suárez [18], Khalil et al. [19] and Xiong el al. [20]. In addition, relying on UBC [1], Salama [21] generated a new equation for building fundamental period based on experimental measurements:

$$T = 0.021.N^{0.16}.H^{0.75} \tag{4}$$

On the other hand, Penzien [22] suggested parametrically an equation to calculate the effective period for inelastic behavior of buildings when structural stiffness is decreased and fundamental period is naturally increased. The equation is expressed as:

$$T_n = T.\phi \tag{5}$$

In this equation, T_n and T are inelastic and elastic building period and ϕ obtained by the following relationship:

$$\phi = \sqrt{\frac{\mu}{\gamma + \beta.(\mu - \gamma)}} \tag{6}$$

Where μ denotes the ductility demand of the structure, β is a value between the ultimate and initial stiffness, γ is recommended to be 1.54. In order to simplify the Equation (6), Kasai et al. [23] modified a value of ϕ based on the ductility demand which is obtained as:

$$\phi = (1 + 0.18.(\mu - 1)) \tag{7}$$

In recent years, some relationships have been also proposed to calculate the structural fundamental period [24-43]. As nearly all equations present fundamental period for regular buildings, undoubtedly the structural period is different for irregular building with the same story. Thus, given the importance and prevalence of irregular buildings, in this study, the structural vibration period for all buildings, including regular and irregular, is considered to determine and compare with both categories. Accordingly, five buildings of 1 to 5 stories are logically modeled considering regular and irregular configurationin height. Besides, ten ground motion records are also selected to examine building vibration period. Using an iterative procedure and artificial neural network (ANN) as a computing system, all structural properties, such as mass, stiffness, overall height and the number of story are defined as inputs and, consequently, the equations are parametrically solved. The modeling results are listed to analyze by ANN again, anda new relationship is generated to determine building vibration period considering all effective parameters.

There are different methods which can be used to predict various types of phenomena, including decision trees and risk analysis statistics and random algorithms or artificial intelligence and machine learning. The process of prediction of the peak lateral displacement of building under earthquake excitation is presented in this paper using the ANN and the investigation is conducted to confirm the accuracy of the method.

Many researchers have confirmed that the use of ANN is an appropriate tool to predict different phenomena [44-48]. In order to create an algorithm predicting the peak lateral structural displacement, it is necessary to build an artificial neuron. The process of building network consists of three basic steps: learning, validation and testing. The first step is to create a database necessary to start building of the algorithm. For this purpose, the properties of the structural model are firstly presented. Then, numerical study, focused on collecting samples to the network, is shown. In the last step, the created networks are presented.

2. Proposed relationship

As the aim of current study is to focus on building vibration period, two reference models are basically considered having one to five stories. The height of each story is assumed to be 3.00 m and the plan of models is considered to be square with 20 m in both directions. The mass of 42500 kg and structural stiffness of 2×10^6 kg/m^2 are assigned for each story of regular model. First models category is regular and second one is modeled to be irregular in height. In order to design the model, columns and beams, Iranian Concrete Code [49] is used. In order to make irregularity, the plan of stories is decreased story by story based on Table 1 and Figure 1. The mass and stiffness of 1, 2, 3, 4 and 5-story irregular model are 42500, 34000, 27200, 21760 and 17400 kg and 2×10^6, 1.6×10^6, 1.3×10^6, 1×10^6 and 0.8×10^6 kg/m^2, respectively.

Table 1. Plan dimensions of the irregular models.

	Story No. 1	Story No.2	Story No.3	Story No.4	Story No.5
1-Story	20×4	-	-	-	-
2-Story	20×8	20×4	-	-	-
3-Story	20×12	20×8	20×4	-	-
4-Story	20×16	20×12	20×8	20×4	-
5-Story	20×20	20×16	20×12	20×8	20×4

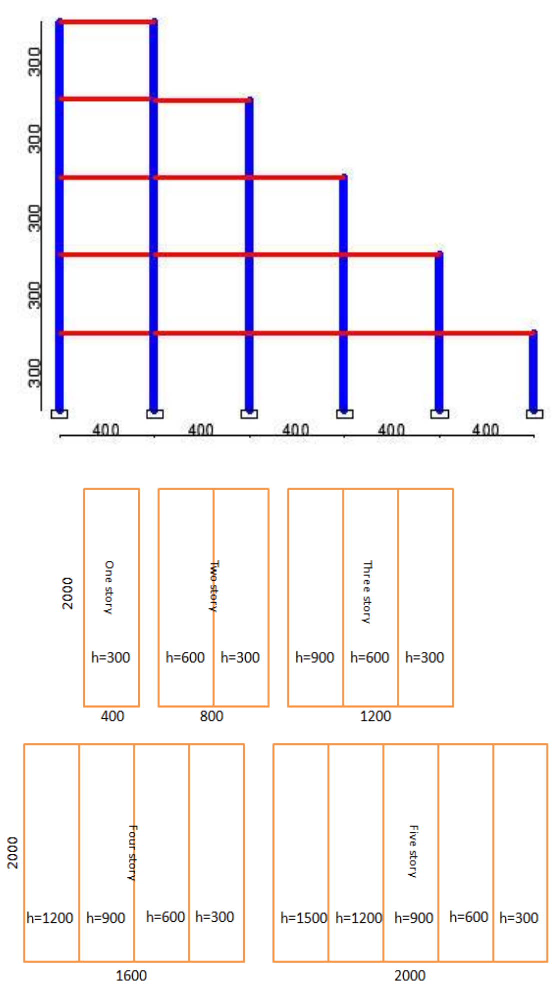


Fig. 1. Elevation and planof irregular model (The unit is cm).

Models are analyzed with ten earthquake records, which are El Centro, Parkfield, San Fernando, Tabas, Landers, Kobe, Kocaeli, Bam, Van and Nepal. The properties of selected records are listed in Table 2.

In order to evaluate building vibration period and make models to analyse with different earthquake records, a part of artificial neural network is considered and subsequently, a particular mathematic program is developed. The developed program is able to model different structures with various stories and configurations to show lateral displacement during seismic excitations. In this program, mass and stiffness of each story, earthquake records, the properties of structures and elements are defined as inputs and the program is parametrically started to solve all equations and matrices to find building vibration period as output.

For this purpose, in each analysis, top story displacement of each model is accurately evaluated using developed program and the time of a completed sway is optimally extracted during earthquake, which is theoretically considered to be building vibration period. Five regular and irregular models with ten earthquake records are numerically analysed and the results of lateral displacements are depicted. The difference of two points with zero displacement, which are located at the start and end of a completed cycle, is regarded as experimentally building period (EBP). The analyses are specifically implemented for all models and earthquake records and finally, EBFs are calculated. On the other hand, five mass-stiffness matrices are developed as a solution for one to five story models to analyse and calculate mathematically building period (MBP). The calculations are carried out for both regular and irregular models to solve matrices and find MBPs.

A series of models with different stories and earthquake records are analysed so as to measure EBPs and parallel to the mentioned solution, matrices are considered. The height of models, number of stories, mass and stiffness of stories, PGA, EBPs and MBPs are recorded as main inputs and listed to enter for ANN program (Figure 2).

Table 2. Characteristics of selected ground motion records.

	Earthquake	Date	Magnitude (M_w)	Station	PGA (cm/s^2)
1	El Centro	1940	6.9	El Centro	307
2	Parkfield	1966	6.2	Jennings (CGS)	462
3	San Fernando	1971	6.6	Pacoima Dam	1202
4	Tabas	1978	7.4	Tabas	911
5	Landers	1992	7.3	Baker	853
6	Kobe	1995	7.2	JMA	817
7	Kocaeli	1999	7.6	Sakarya	369
8	Bam	2003	6.6	Bam	780
9	Van	2011	7.2	Muradiye	491
10	Nepal	2015	7.8	KATNP	641

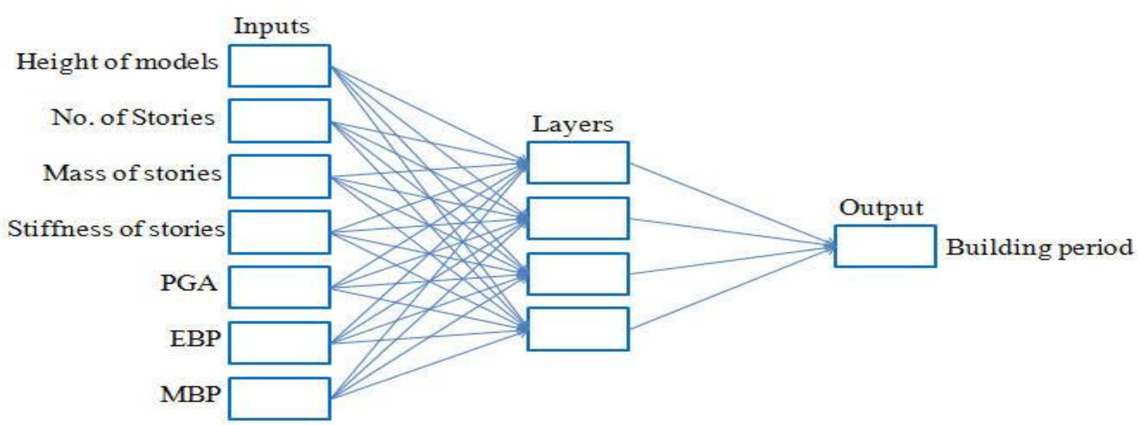


Fig. 2. Schematic presentation of ANN model.

The ANN has been used so as to determine building vibration period of the models with different properties (Height of model, number of story, mass and stiffness of stories, peak ground acceleration, experimental building period and mathematical building period) exposed to earthquakes with various PGA. The output is the predicted building vibration period. Based on all inputs and learned trend of solution to calculate the building vibration period, the ANN has been applied to start the trend and coordinate all inputs, solve in hidden layer and finally, calculate building vibration period as output. Firstly, irregular models are analysed with different earthquake records and EBPs are calculated. The results of analyses are seen in Tables 3 and 4. The means of EBPs are 0.92, 1.18, 1.38, 2.01 and 2.39s for one to five story models with different earthquake records, respectively. Secondly, using mass-stiffness matrix, MBPs are determined and the results are compared with EBPs. For this challenge, there is a normal matrix for different stories, which is written as below, for instance, for 3-story model:

$$\begin{bmatrix} k_3+k_2 & -k_2 & 0 \\ -k_2 & k_2+k_1 & -k_1 \\ 0 & -k_1 & k_1 \end{bmatrix} - \omega^2 . \begin{bmatrix} m_3 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_1 \end{bmatrix} = 0 \quad (8)$$

The results of analyses have been collected and listed in Table 3.

Table 3. The results of building vibration periods for both models.

	Regular model		Irregular model	
	EBP	MBP	EBP	MBP
1-Story	0.92	0.92	0.92	0.92
2-Story	1.19	1.194	1.18	1.182
3-Story	1.41	1.432	1.38	1.398
4-Story	2.05	2.07	2.01	2.05
5-Story	2.41	2.44	2.34	2.39

The results of EBPs and also MBPs have shown that building vibration period of regular models are more than irregular models which depends significantly on the mass and stiffness of models. As the overall height and the number of story of both models (regular and irregular) are same, thus, mass and stiffness are so important to calculation of building vibration period.

Each model has approximately shown a mutual value of building vibration period for different stories which are so close to each other in EBP. As it is obviously seen in Tables 3 and 4, building vibration periods are approximately same among different earthquake records which indicate the properties of earthquake is not effective in building period. Therefore, building vibration period depends naturally on the internal characteristic of structures, which can be related by:

$$T \cong f(H, N, m, k) \quad (9)$$

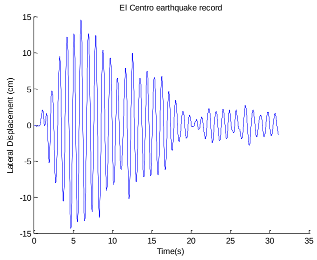
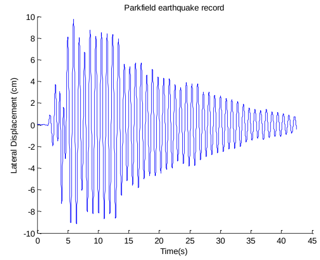
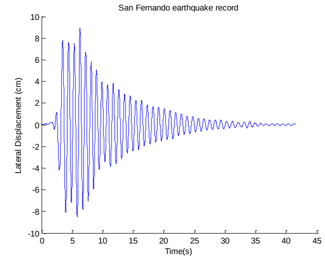
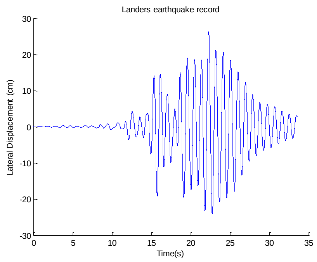
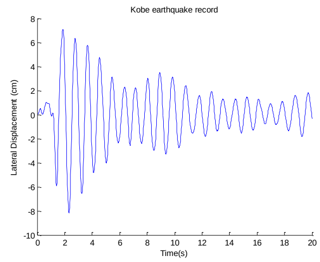
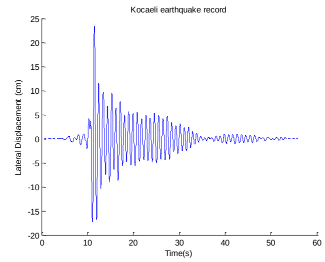
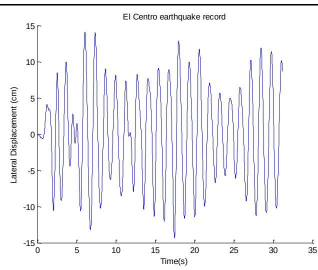
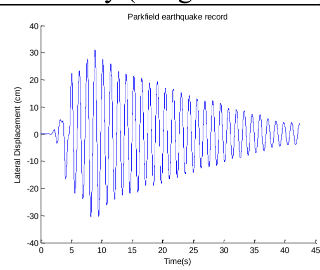
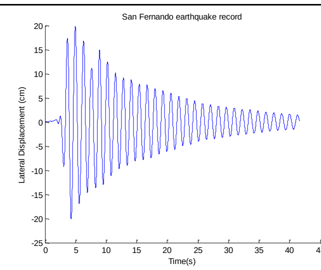
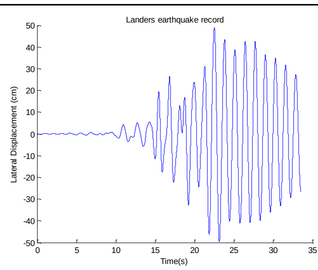
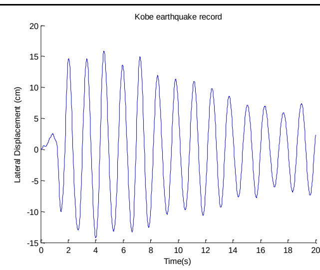
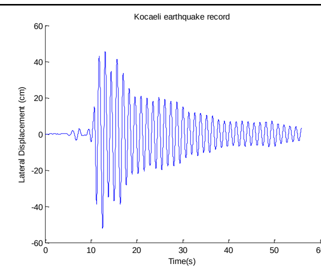
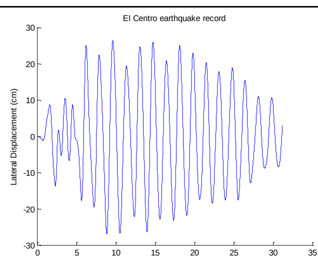
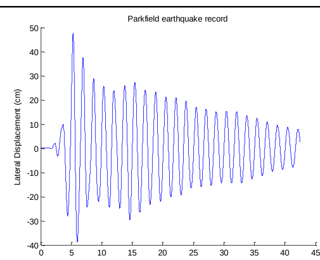
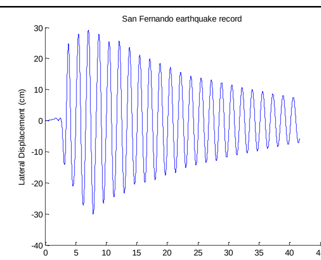
According to EBPs, MBPs and all needed parameters, a value of building vibration period is randomly predicted and an iterative procedure is started by ANN. Height, number of stories, mass and stiffness of each story are considered and then, a value of different factors is selected. The building vibration period is determined and compared with original estimated building period.

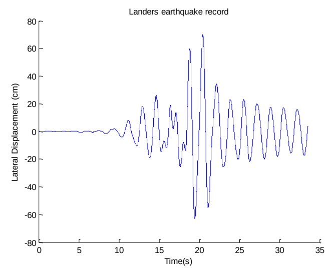
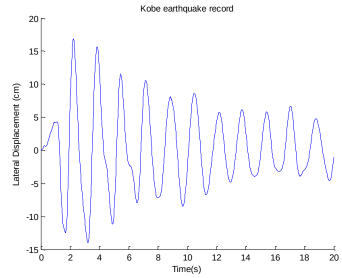
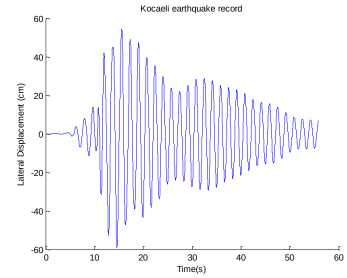
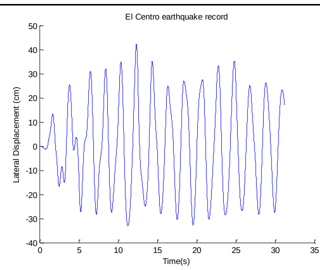
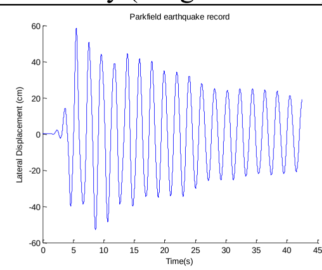
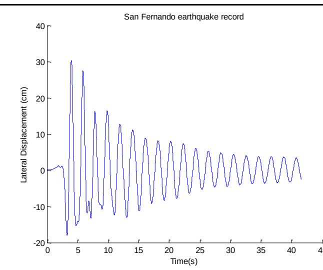
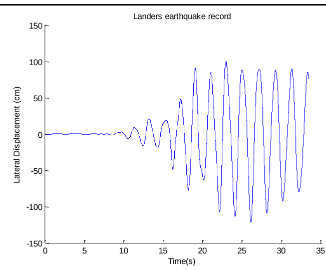
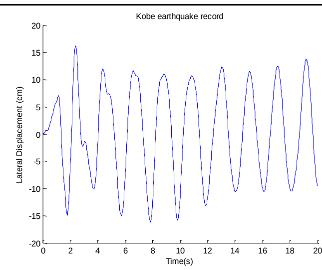
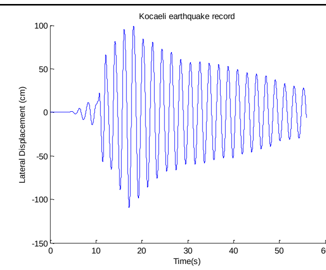
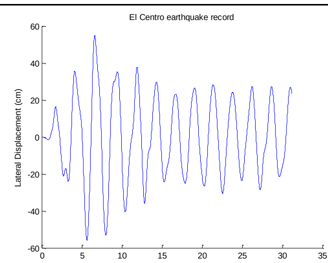
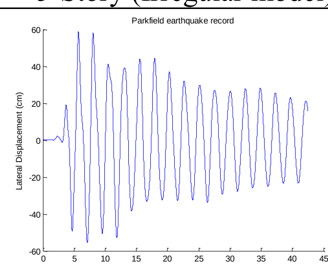
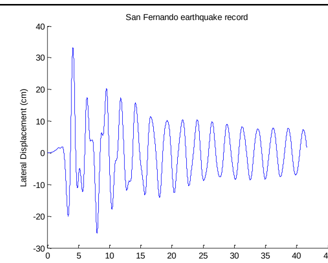
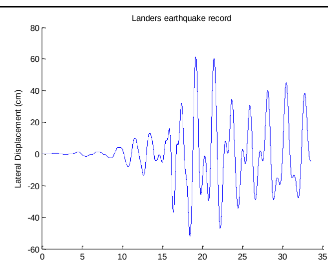
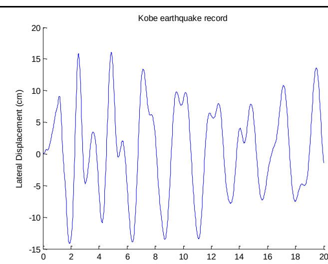
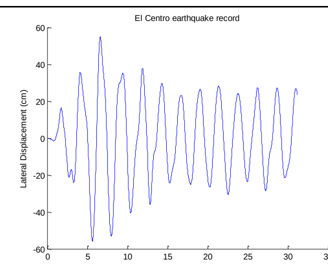
When both building periods are same or close to each other, program automatically select the factor as output and continue procedure to suggest final equation by a special regression. MBPs and building periods, calculated by ANN, are depicted and compared with each other in Figure 3.

In order to suggest a relationship to determine building vibration period, all inputs are taken by ANN and analysed to organize building period relying proposed procedure (Figure 4). For this purpose, MEPs, the overall height of model, the number of stories, mass and stiffness of each story are informed as inputs and program starts a cyclic process. Firstly, two values of α and μ are randomly estimated and the formula, based on overall height of model is solved. Then, calculated period is compared with MEP, if the results are same, second step is automatically started by program and if no, a new values of α and μ are considered and solution is repeated. The process is continued to get final results and formula.

After completion iterative procedure, a new relationship is generated to calculate building vibration period which can be written as a general form (Equation 10):

Table 4. The results of analyses for different models.

	1-Story (Irregular model)		
			
EBP	0.921	0.919	0.92
			
EBP	0.92	0.921	0.92
	2-Story (Irregular model)		
			
EBP	1.179	1.174	1.18
			
EBP	1.184	1.182	1.181
	3-Story (Irregular model)		
			
EBP	1.383	1.378	1.38

			
EBP	1.38	1.379	1.382
	4-Story (Irregular model)		
			
EBP	2.01	2.014	2.00
			
EBP	2.018	2.012	2.013
	5-Story (Irregular model)		
			
EBP	2.345	2.341	2.292
			
EBP	2.34	2.345	2.297

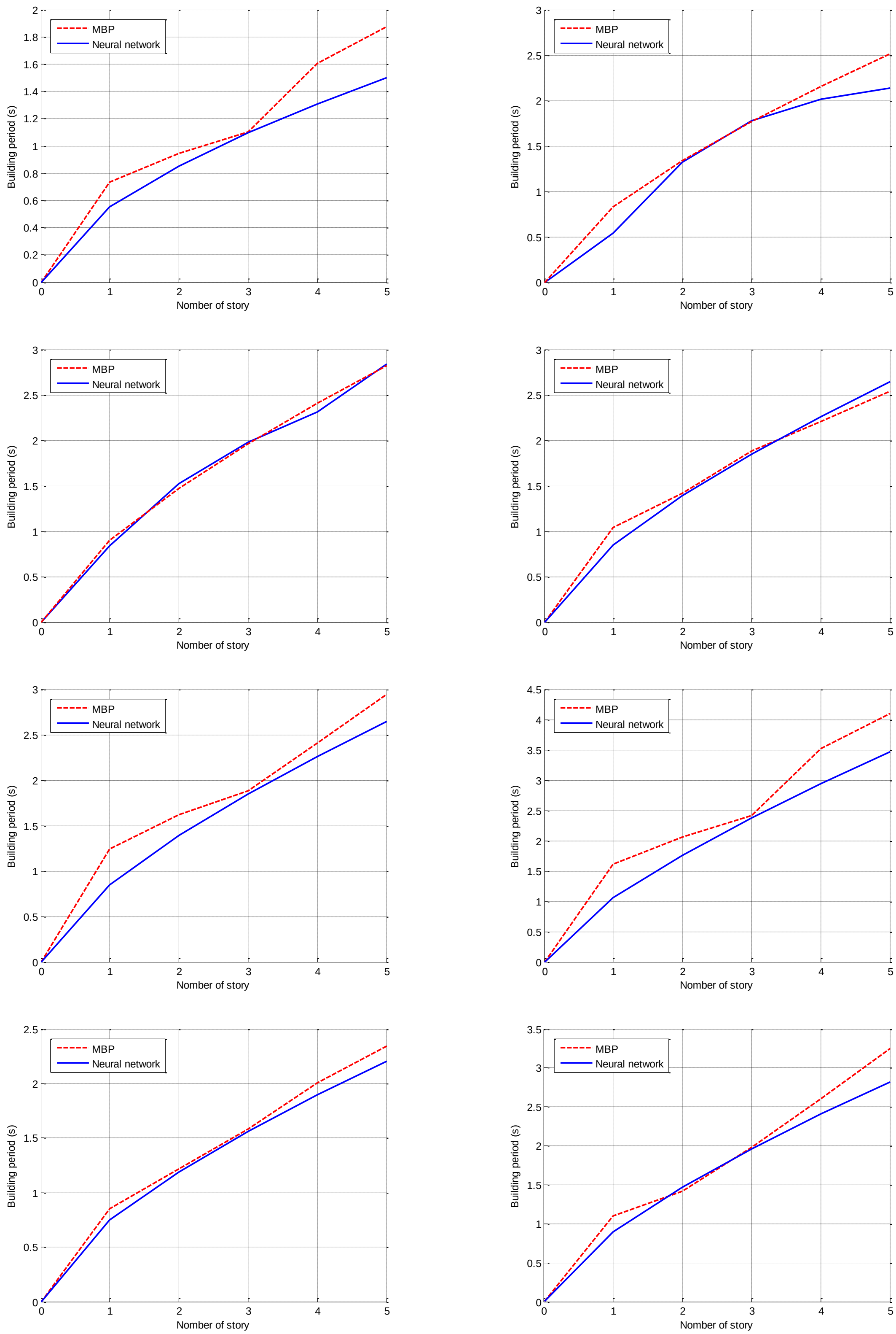


Fig. 3. Comparison of MBPs and building periods, calculated by ANN.

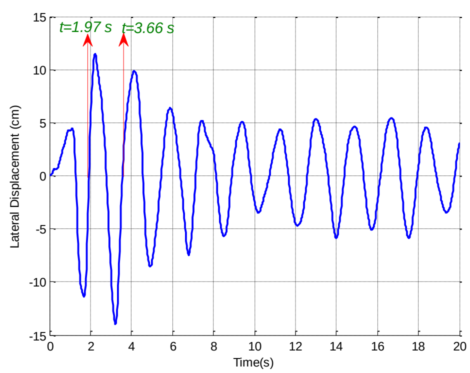
$$\begin{cases} T = 0.021.(H)^{0.66}.(\sum_{i=1}^{N}\left(\frac{M_i}{K_i}\right))^{0.008}.N^{0.0546} \rightarrow Regular \\ T = 0.0219.(H)^{0.63}.(\sum_{i=1}^{N}\left(\frac{M_i}{K_i}\right))^{0.008}.N^{0.0576} \rightarrow Irregular \end{cases}$$

$* H(cm)$ (10)

3. Accuracy of the proposed relationship

In order to evaluate the accuracy of the proposed relationship, numerical analyses for regular and irregular 3-story model are carried out to determine building vibration period. Firstly, using Kobe earthquake record, an irregular 3-story model with a mass of 38500, 31000 and 23200 kg and stiffness of 2×10^6, 1.6×10^6 and 1.2×10^6 kg/m^2, for first, second, and third stories, respectively, is considered.

$$\begin{bmatrix} 2+1.6 & -1.6 & 0 \\ -1.6 & 1.6+1.2 & -1.2 \\ 0 & -1.2 & 1.2 \end{bmatrix} * 10^6 - \omega^2 . \begin{bmatrix} 38500 & 0 & 0 \\ 0 & 31000 & 0 \\ 0 & 0 & 23200 \end{bmatrix} = 0 \rightarrow Calculation \rightarrow T = 1.765s$$



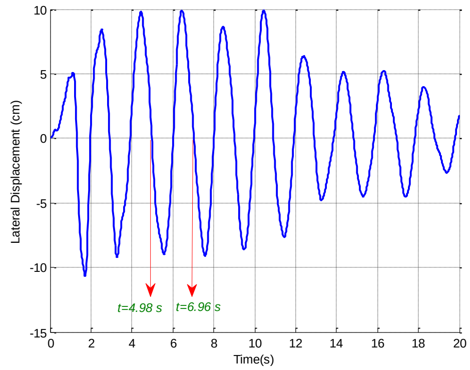
$$T = 1.69s$$

$$T = 0.0219.(H)^{0.63}.(\sum_{i=1}^{N}\left(\frac{M_i}{K_i}\right))^{0.008}.N^{0.0576} \rightarrow T = 1.66s$$

As it is seen, proposed relationship has mathematically calculated a building vibration period about 1.66s, which is 1.765s and 1.69s for MBP and EBP, respectively.

In the following, regular 3-story model is assumed with a lumped mass of 38500 kg as well as stiffness of 2×106 kg/m^2 and building vibration period is calculated using three different ways.

$$\begin{bmatrix} 2+2 & -2 & 0 \\ -2 & 2+2 & -2 \\ 0 & -2 & 2 \end{bmatrix} * 10^6 - \omega^2 . \begin{bmatrix} 38500 & 0 & 0 \\ 0 & 38500 & 0 \\ 0 & 0 & 38500 \end{bmatrix} = 0 \rightarrow Calculation \rightarrow T = 1.96s$$



$$T = 1.98s$$

$$T = 0.021.(H)^{0.66}.(\sum_{i=1}^{N}\left(\frac{M_i}{K_i}\right))^{0.008}.N^{0.0546} \rightarrow T = 1.94s$$

As it is obviously seen, proposed relationship has mathematically calculated a building vibration period about 1.94s, which is 1.96s and 1.98s for MBP and EBP, respectively.

So, the average of EBP and MBP is 1.72s for irregular model which is calculated to be 1.66s by proposed formula and is 1.97s for regular model that is 1.94s by proposed formula.

The results of both models are close to each other which show the proposed equation can be accepted and confirmed for determining the building vibration period in different building configurations.

4. Numerıcal analyses

In order to compare the building vibration period from some past equations and suggested relationship, numerical analyses are implemented for regular model with different stories, same lumped mass and structural stiffness.

The measured building period based on different equations are graphically depicted and compared with each other in Figure 5. According to the Figure 6, ASCE 7-10 has shown the maximum value of building period, which is 4.23s for 5-story building. Other codes have determined a value of 3.13s and 2.61s for 5-story building while this parameter is 2.82s and 2.83s using proposed relationship and Salama (2013). In fact, building vibration period, calculated by proposed formula, is about 8% more than ATC3 and 9% less than UBC, SEAOC and NEHRP. Proposed formula, UBC, SEAOC, NEHRP and ATC3-06 have shown the results near to each other, which can confirm the results of proposed formula.

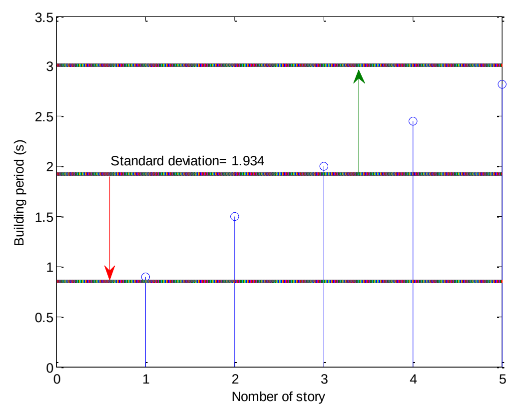


Fig. 5. Standard derivation of proposed formula.

As it is seen in the figure 5, standard derivation of proposed formula is calculated, which indicates that all building periods are imitated from 0.859s to 3.00 s.

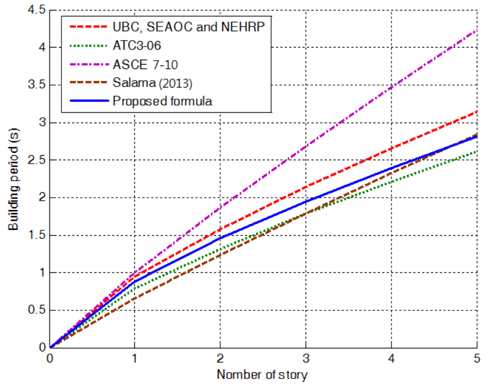


Fig. 6. The results of building vibration period using different equations.

4.1 Effect of structural mass and stiffness

In this section, the influence of structural mass and stiffness on the building vibration period is numerically investigated using proposed equation. For this purpose, the value of $(Mass/Stiffness)$ is considered to be changed from 0 to 1, while overall height and number of stories are constant.

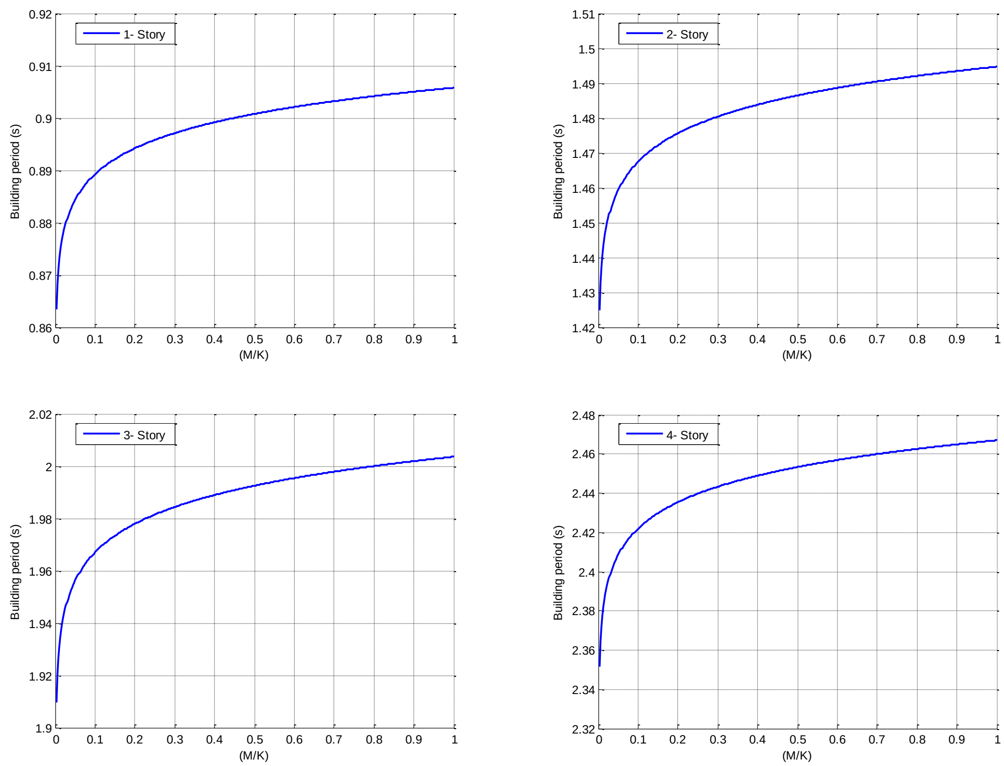
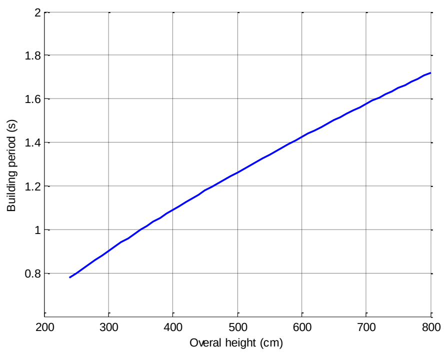


Fig. 7. The results of building vibration periods for different mass and stiffness.

As it is seen from Figure 6, the difference between the minimum and maximum value of building periods are 0.0424, 0.045, 0.094 and 0.115s for one-, two-, three- and four-story models, respectively. It indicates indeed that by increasing overall height or the number of stories, the effect of stories mass and stiffness is suddenly increased (the difference is 0.132 and 0.155 for five- and six-story).

4.2. Effect of overall height and number of stories

In order to investigate the effect of overall height and similar stories and also various number of stories and similar overall height, firstly, a one-story model is considered and the value of overall height is suggested to be different from 240 to 800 cm ($\frac{m}{k}=0.5$). In fact, the effect of overall height and number of story is considered to be investigated. The analyse is carried out and the results are listed. Minimum building vibration period is 0.785s and maximum value is 1.73s, which have a difference value of 0.96s. On the other hand, an overall height of 960 cm is assumed for one-, two-, three-, and four-story models. The results demonstrate that building vibration period is 1.941, 2.02, 2.08 and 2.117s for different stories with the same overall height.



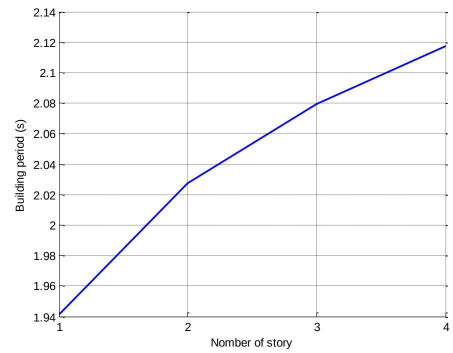


Fig. 8. The results of building periods for different overall height and number of stories.

The results have been seen in Figure 7, which shows building vibration periods with different overall height and number of stories. It seems that the structural height has the biggest effect among other parameters in order to determine building vibration period. Increasing overall structural height without considering other parameters causes a rapid increase in the building vibration period.

5. Conclusions

In this study, a new relationship was proposed to determine building vibration period for regular and irregular buildings in height using artificial neural network (ANN). The proposed equation covers the majority of effective parameters such as height, mass and stiffness of each story as well as number of stories. In order to develop the equation, five models with one to five stories and ten earthquake records were considered and lateral displacement were extracted. Relying on the results, building vibration period (EBP) was calculated, which is assumed to be the time of a completed sway of top level of building models. Subsequently, mass-stiffness matrix of each model was developed and building vibration period was calculated (MBP). Using building periods and characteristic of models, an iterative procedure was mathematically started by ANN. Accordingly; a new value was logically predicted for building period to justify the period based on all needed parameters. The influences of overall height, number of story, mass and stiffness of buildings were also evaluated, which indicates that overall height is the most effective among other parameters. For this purpose, a cyclic process is written and parameters are considered to make a combination as proposed formula to calculate building vibration period. Different model by having various stories, mass, stiffness and also overall height are evaluated and their building vibration periods are numerically calculated by three different ways to compare among them. Finally, the accuracy of proposed relationship was numerically investigated and confirmed using comparison with other models and proposed code equations. Proposed formula, UBC, SEAOC, NEHRP and ATC3-06 have shown the results near to each other, which can confirm the results of proposed formula. Calculated period is 8% more than ATC3 and 9% less than UBC, SEAOC and NEHRP.

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