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FASTER TIME INTEGRATION ANALYSIS FOR BUILDING STRUCTURS SUBJECTED TO 3-COMPONENET EARTHQUAKES

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Abstract. *Time integration is the most versatile tool to analyze and recognize dynamic behavior of structures. However, besides the versatility and simplicity, the resulting responses are accompanied by many approximations, while the computational efforts are considerable. The main parameter controlling the accuracy and computational cost is the integration step size, a positive definite parameter, uniformly controlling the size of integration steps throughout the integration interval. For an efficient time integration analysis it is conventional to implement integration step sizes as much as small enough to provide sufficient accuracy. An exceptional case is time integration of structural systems, subjected to digitized excitations, when the digitization step size is smaller than the size essential for sufficient accuracy. In such analyses, additional computational cost should be spent, merely to consider the digitized excitations. Recently, a technique to overcome the deficiency is proposed and successfully implemented in time integration analysis of different practical cases, e.g. simple linear and nonlinear examples, tall buildings, bridges, silos, reservoirs. However, in all examples the seismic excitations are considered as one-component records. The aim of this study is to examine the performance of the recently proposed technique in dynamic time history analysis of a building structure subjected to a three-component earthquake record.*

1 INTRODUCTION

In many cases, in order to evaluate real performance of civil engineering structures during extra loadings, in general, using the time integration analysis is inevitable. Nowadays, seismic evaluations and retrofitting design process need deep understanding of the real behavior especially seismic behavior of buildings and bridges during strong ground motions. In this regard, understanding of building performances against natural disaster are only achieved by considering their dynamic time history analysis. Such analyses need some special features like detailed modeling of the building, recognizing realistic loadings may happen in the future, and a comprehensive and consistent analysis method. Also, we know that considering unusual behavior of infrastructures during environmental loadings may not be simplified to static or even pseudo-static evaluations. On the other hand, performing a dynamic time history analysis in real world is accompanied by some errors causing the results to be inexact representing of the real behavior but only an approximate one. Difficulties emerge when we do not know values and sources of errors. Now, it is clearly recognized that in any numerical method, the magnitude of the selected time steps is strongly affect the accuracy and also stability of the step-by-step integration methods. Many analysis methods to ensure satisfying stability criteria need assigning small time steps. Hence, selection of the proper time increment, Δt, is an important problem. Among various effective parameters the two following factors should be carefully considered: (1) the period of the last effective mode of the structure, whcih should be considered in the analysis; (2) the digitization steps of the seismic excitations. If the nonlinear behavior of the system is included in the analysis, nature of the changes of the stiffness and damping matrices during the following steps may be an effective parameter influence on the selection of time step [1].

In general, it is known that sufficiently accurate results can be obtained if the time increment is selected to be no longer than one-tenth of the period of the last effective mode of the structure. However, using step-by-step time integration analyses with so small time step significantly increase the computational costs. Hence, if we can lengthen time steps such that it guarantees the accuracy and stability of the analysis, the size of time step is limited to the values by which, the excitation is recorded. Recently, a technique by Soroushian [2] is proposed for decreasing the computational cost in which, size of the time steps of a recorded earthquake ground motion is lengthen without changing other characteristics of the record. In 2010, Soroushian [3] used this method for considering linear and nonlinear behavior of a single degree of freedom excited by an earthquake record. In this paper, we aim to evaluate this method for a 3-componenet earthquake when applied to an 8-story 3-dimensional building using conventional time integration methods. A brief review of the recent technique is presented in the following section.

2 THE RECENT TECHNIQUE IN BRIEF

According to Soroushian [2], in order to replace the original excitation with a new digitized excitation with larger steps such that the responses rate of convergence is preserved four steps are designed as follows:

1- The excitation steps, ${}_f\Delta t_i \; i = 1,2,\dots$, are equally sized,

2- The integration steps, $\Delta t_i \; i = 1,2,\dots$, are equally sized,

3- The excitation steps are embedded by the integration steps (the first time station, i.e. t_0, is a station for both excitation and integration),

4- If we assumed that $\mathbf{f}(t)$ is a digitized representation of an actual excitation we can replace it with a new excitation, $\tilde{\mathbf{f}}$, digitized at steps equal to n times larger, according to:

$$\begin{aligned} t_i = 0: &\quad \tilde{\mathbf{f}}_i = \mathbf{f}(t_i), \\ 0 < t_i < t_{end}: &\quad \tilde{\mathbf{f}}_i = \frac{1}{2}\mathbf{f}(t_i) + \frac{1}{4n'}\sum_{k=1}^{n'}\left[\mathbf{f}(t_{i+k/n}) + \mathbf{f}(t_{i-k/n})\right], \\ t_i = t_{end}: &\quad \tilde{\mathbf{f}}_i = \mathbf{f}(t_i), \end{aligned} \tag{1}$$

where,

$$\begin{aligned} t = \Delta t: &\quad n' = n - 1 \\ \Delta t < t < t_{end} - \Delta t: &\quad n' = \begin{cases} \dfrac{n}{2} & n = 2j \quad j \in Z^+ \\ \dfrac{n-1}{2} & n = 2j+1 \quad j \in Z^+ \end{cases} \\ t = t_{end} - \Delta t: &\quad n' = n - 1 \end{aligned} \tag{2}$$

and Δt and n ($n \in Z^+$) are the largest values such that accuracy of the results and stability of the method are satisfied with generally accepting a small loss of accuracy in time integration. Since, the new excitation, $\tilde{\mathbf{f}}$, is digitized at steps equal to $n_f \Delta t$, when considered instead of the original excitation, can lead to a reduction in computational cost including the time spent and memory, which is essential for the analysis.

3 STRONG GROUND MOTION

On Jun-20-1990, a destructive earthquake occurred in Gilan and Zanjan provinces. The strongest ground motions of this earthquake have been recorded at the Abbar station at a 10 km distant from earthquake fault. [4]. In this research, the three components of this earthquake, *i.e.* longitudinal, transversal, and vertical directions, which are digitized by a time step equal to 0.005 sec is used as the strong ground motion. Using the new proposed method [2] the three components of the Abbar earthquake records are digitized at steps 2, 3, 4, and 10 times larger than the steps in the original records, *i.e.* 0.01, 0.015, 0.02, 0.05 sec. Filtering or baseline correction are not applied on the new digitized records. The acceleration records derived from the longitudinal direction of the earthquake record for various time steps are separately shown in Figure 1. By visual comparing the new digitized records in Figure 1, it can be seen that configuration of the records are preserved except for the last one, *i.e.* time step 0.05 sec. The time history of the velocity and displacements derived from the acceleration digitized records by carrying out a numerical integration process, are shown in Figure 2. It is mentioned that the velocity and displacement of the digitized record with 0.05 sec. step size, show slight and major differences respectively with respect to the other related results. It emphasizes our previous visual conclusion.

In order to better understanding the changes occurred in the new digitized records their other characteristics of this direction are compared. The response spectra of the digitized records are considered in Figure 3. This figure shows the maximum acceleration response of a single degree of freedom system against the longitudinal direction of the digitized records. It is seen that large time steps, like 10 times larger, may lessen the power of the short periods of the main record. It is because if sampling rate of the new digitized record is assumed to be 0.05 sec, the Nyquist frequency is 10 Hz, the modes with periods shorter than 0.1 sec are not considered in the record, and they may produce conflict in the results. This may observe in the acceleration and velocity responses of systems. So, we expect that the results related to this record because unexciting high frequency modes of the building model in comparison to the other digitized records produce farther results with respect to the original record.

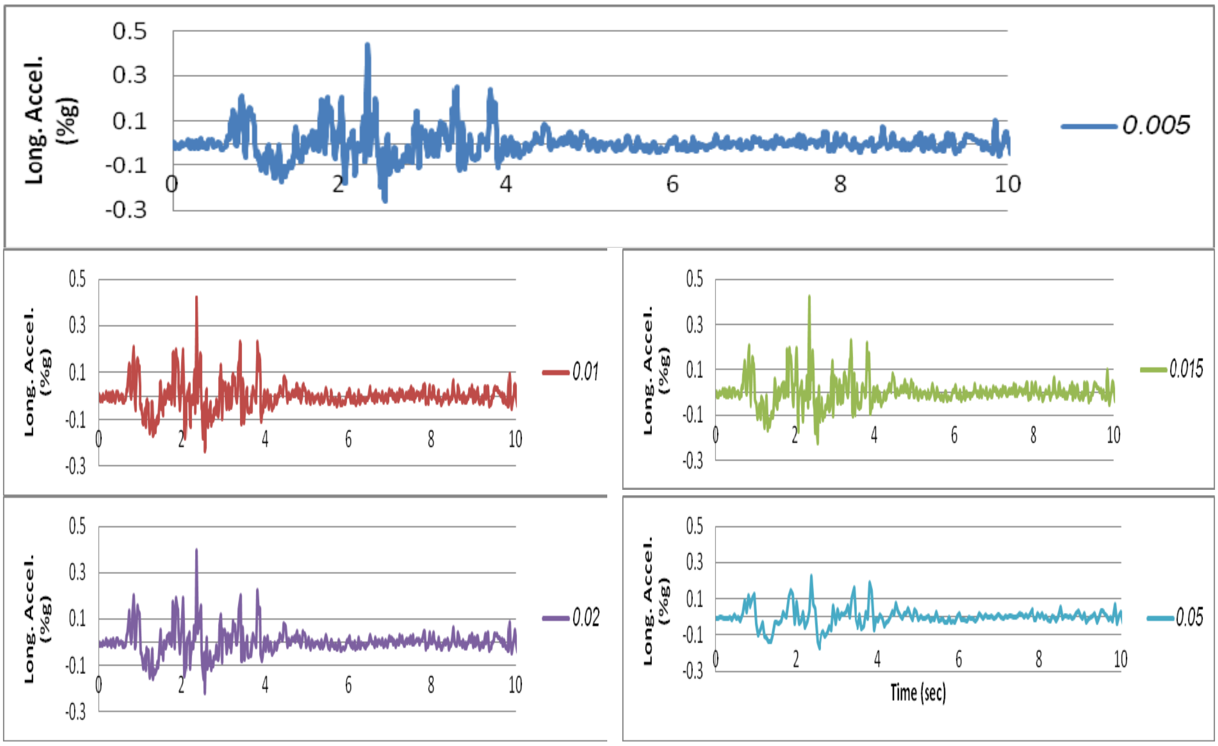

Figure 1: The digitized acceleration records of the longitudinal direction with various step sizes.

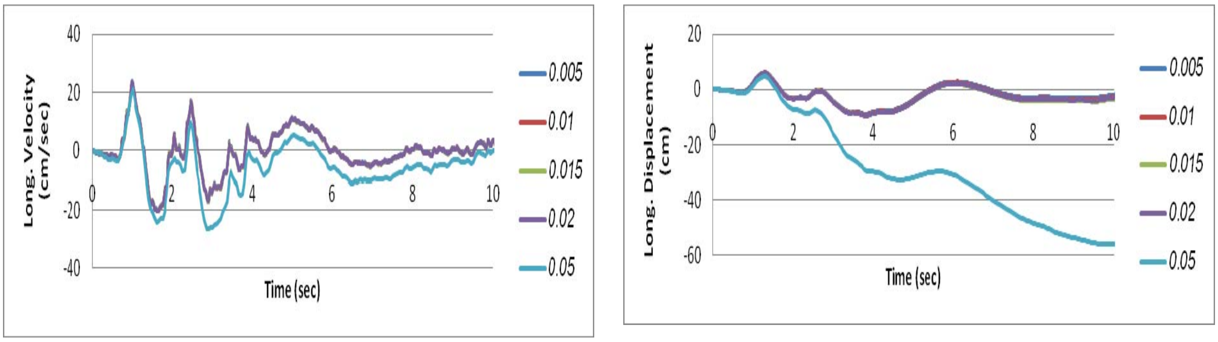

Figure 2: The digitized velocity (left) and displacement (right) records of the longitudinal direction with various step sizes.

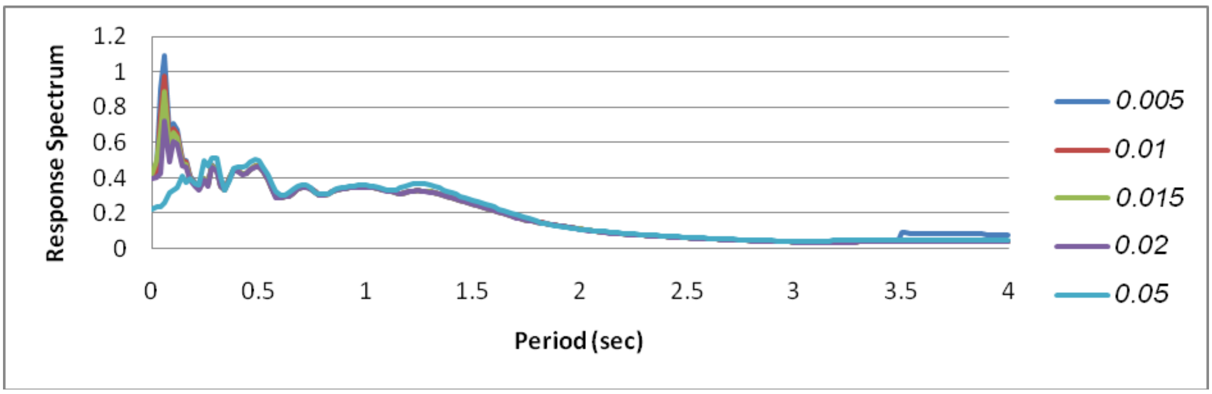

Figure 3: The response spectrum of the longitudinal direction of the digitized records with various step sizes.

Arias intensity drawn in Figure 4 (left side), is a ground motion parameter that captures the potential destructiveness of an earthquake as the integral of the square of the acceleration-time history. It correlates well with commonly used demand measures of structural performance, and several demands related to geotechnical appearances like liquefaction and seismic slope stability. Arias intensities in Figure 4, shows that we may suppose that the performance of the building against digitized records with various time steps are not so different. Energy flux drawn in Figure 4 (right side) is the total rate of energy transfer through a surface. The results show that the rate of transferring energy to the building due to the digitized record by time step equal to 0.05 sec is completely different from the other records. Hence, it may cause the response of the building to be more excited at the end of the mentioned record. It is emphasized that performance of the building due to the other digitized records will be very similar.

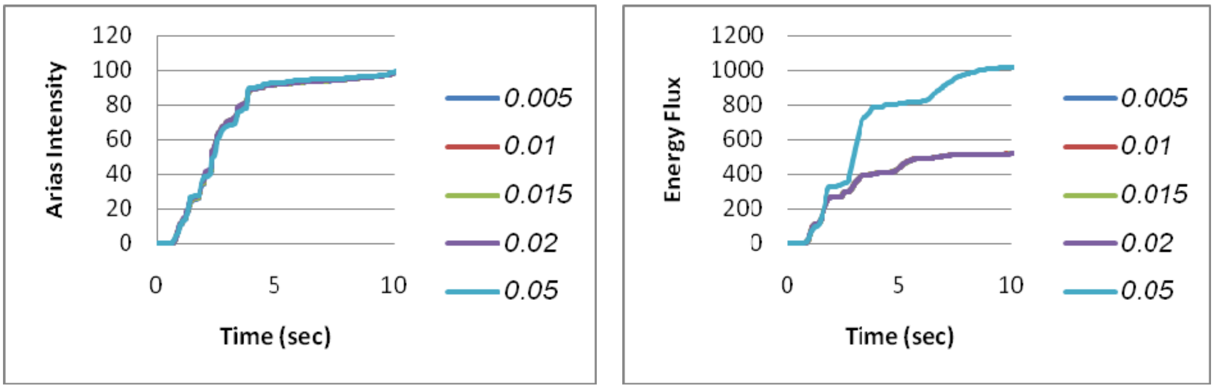

Figure 4: Arias intensity (left) and energy flux (right) related to the longitudinal direction of the digitized records with various step sizes.

The maximum acceleration, velocity, and displacement of the digitized records with various time steps presented in Table 1 are compared with the values of the original record. The results show that the main characteristics of the digitized records with time steps even 4 times larger than the original one are not seriously changed. It refers to the power of the new proposed method to re-digitized records by using larger time steps [2]. Hence, it is recognizable that the response of the building may not so change until time steps 4 times larger but it may completely different when using 10 times larger time step. Meanwhile, using combination of the three components of the earthquake records may slightly affect our guesses.

Table 1: The maximum ground acceleration, velocity, and displacement of the records digitized by various time step sizes.

Time step (Sec)	0.005			0.015			0.020			0.05		
Dir.	L	T	V	L	T	V	L	T	V	L	T	V
PGA (%g)	0.44	0.32	0.30	0.42	0.30	0.26	0.40	0.29	0.25	0.22	0.25	0.20
PGV (cm/sec)	23.67	40.06	30.54	23.35	39.70	30.34	23.11	39.34	30.09	26.56	37.69	39.10
PGD (cm)	9.22	131.13	107.74	9.63	129.00	107.13	9.65	127.97	105.50	57.35	135.08	203.72

4 NUMERICAL STUDY

In this section, seismic behavior of an 8-story 3-dimensional steel structure against different 3-component earthquake records digitized by assuming various time steps is presented.

The building is symmetric about X and Y directions, includes four special moment resisting frame in each direction, and eight equal height floors. It has three equal spans 5 meters length in each direction, and each floor height is assumed to be 3 meters. This building is designed according to the Iranian codes [5-7]. Using the linear dynamic time history analysis, seismic evaluation of the building against the 3-component original earthquake records and the digitized earthquake records with 2, 3, 4, and 10 times larger than the original step size are carried out. The acceleration and displacement responses of the top floor of the building in X-direction due to the different 3-componenet digitized earthquake records are shown in Figure 5. Although, one may observe some dispersion in the acceleration response of the top floor due to unconsidered higher modes, but the displacement response is very smooth and similar for different time steps such that the differences of maximum values in each cycle are not assessable. It is because the displacement responses are highly influenced by the excitation of the lower modes of the building.

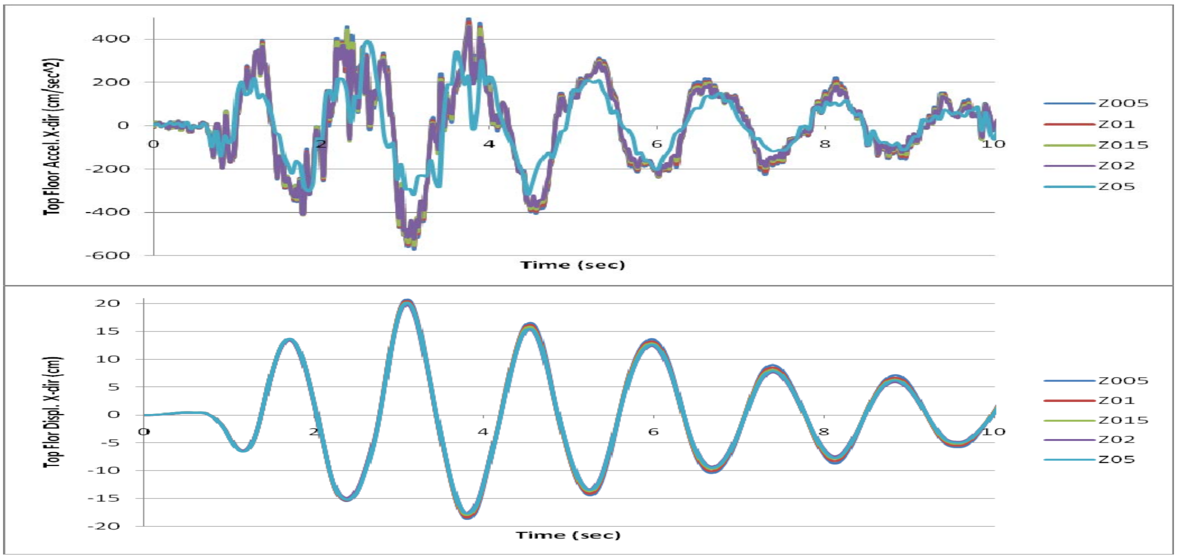

Figure 5. The acceleration (up) and displacement (below) responses of the top floor in X-direction during different 3-componenet digitized earthquake records.

The base shear responses of the building in X-direction due to the different 3-component digitized records are shown in Figure 6. It appears that they are almost identical. It is reasonable because the base shear variations to a great extent follow changes in the displacement responses. So, we may expect that almost all the results show good agreement with the responses of the building due to the original 3-component earthquake record.

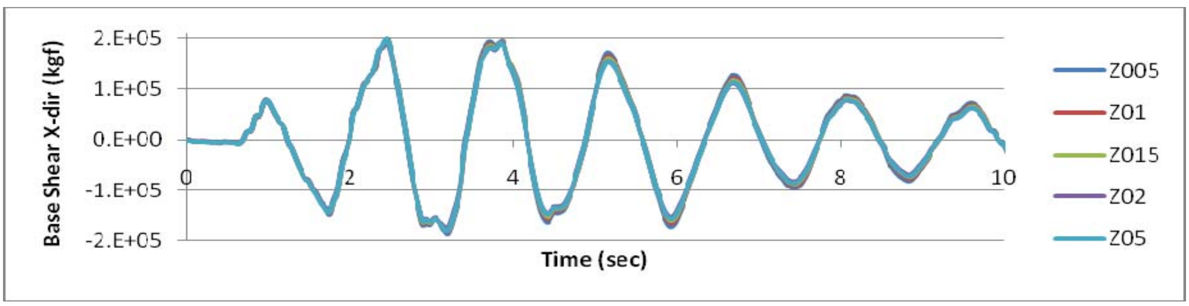

Figure 6. The base shear responses of the building structure in X-direction during different 3-componenet digitized earthquake records.

Figure 7 shows the maximum displacements of the even floors in positive (right) and negative (left) directions. The values are very similar even for step size 10 times larger. There is only a slight decrease in the responses due to 4 and 10 times larger time steps. But, its differences are not recognizable. Hence, it may conclude that except for the acceleration responses, even using 10 times larger time step may be acceptable and meet the designers' goals.

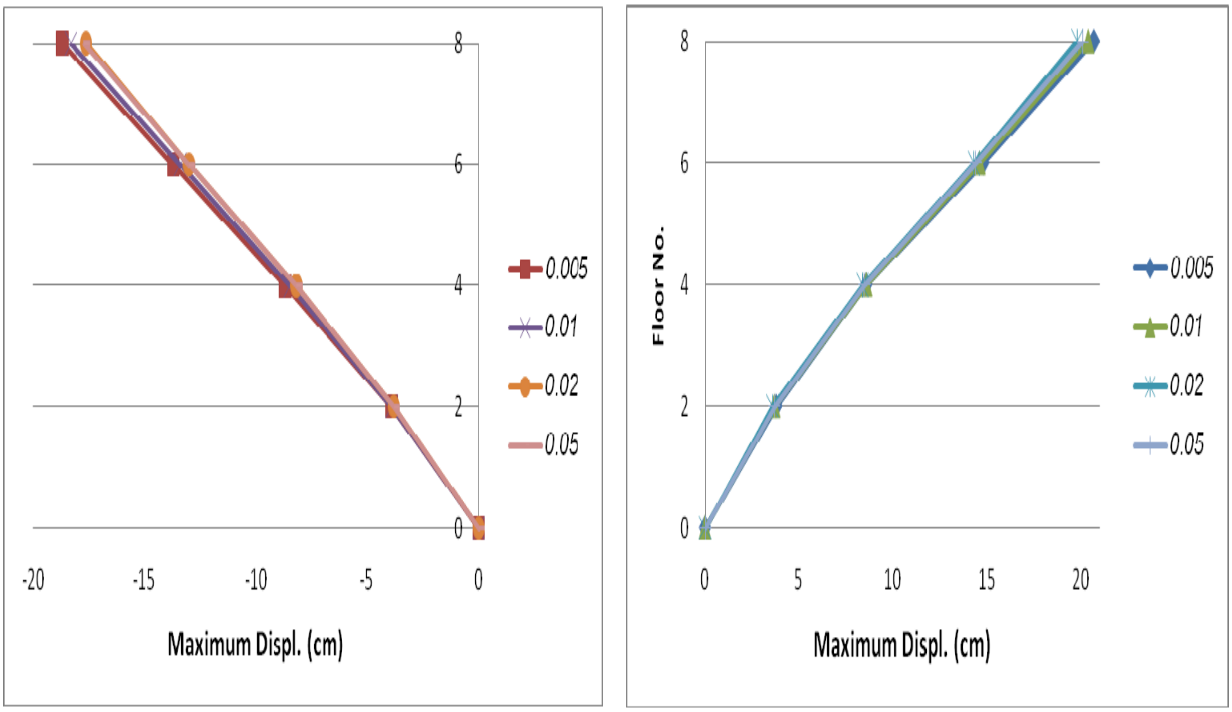

Figure 7. Maximum displacements of the even floors of the building structure in X-direction during different 3-componenet digitized earthquake records.

Now, we consider the error percentages of the acceleration and displacement responses of the top and the 1st floors due to the earthquake records digitized by various time steps. The results are tabulated in Table 2. It is clear that the values of the displacement responses for positive and negative side are very similar to the correct values. It is noticeable that the error related to the step size 4 times larger is greater than that of 10 times larger. However, considering the acceleration responses show that rapidly incorrect increasing the values of the acceleration responses may happen as the step size of the original earthquake record increases. It is because the higher modes are not considered in the analysis.

Table 2: The error percentages of the top and the 1st floors responses due to the earthquake records digitized by various time steps.

Error Value %		0.01	0.015	0.02	0.05
Top floor acceleration response	right side	-3.0	-7.0	-8.2	-11.8
	left side	-3.4	-3.6	-8.2	-6.6
1st floor acceleration response	right side	-4.0	-5.6	-20.2	-18.7
	left side	-4.4	-3.2	-9.0	-43.8
Top floor displacement response	right side	-1.4	-2.9	-4.4	-3.2
	left side	-1.9	-3.8	-5.8	-5.4
1st floor displacement response	right side	-1.4	-2.9	-4.5	-2.6
	left side	-1.1	-2.2	-3.6	-2.2

Finally, the overall time consuming for each analysis are compared in Table 3. Since, the building structure belongs to relative short height building, differences are not effective. Based on the results represented in Tables 2 and 3, it seems using step size 3 times larger presents the best corrected results and decreased time needed for analysis. But, if the acceleration response has not influence in our considering, it may use step size 10 times larger.

Table 3: The time consumes during linear dynamic time history analysis due to the earthquake records digitized by various time steps.

Time Step (sec)	0.005	0.01	0.015	0.02
Run Time	37' 33"	18' 40"	15' 20"	12' 14"

Discussion presented by considering the differences occurred in the inherent characteristics of the new digitized records does not necessarily result in predetermined performance of the building. Because, it is strongly related to the parameter of the considered building, characteristics of the original earthquake even including 1, 2, or 3 components in the analysis, and finally to the conditions and assumptions of the analysis. Some discrepancies may be related to the records before and after regeneration are not corrected by baseline procedure. This may slightly change the characteristics of the digitized earthquakes and influence the performance of the building. But overall, considering the results show that the new proposed method has effective influence on decreasing time consuming and memory used by preserving correctness of the building performance.

5 CONCLUSIONS

In this paper, a new proposed method to regenerating earthquakes by larger step sizes and its influence on seismic performance of a 3-dimensional 8-story special moment resisting frame steel structure is examined. Considered earthquake is the first 10 sec of the 3 components of the Abbar earthquake records. The results are not filtered or baseline corrected. Evaluation of the different parameters and characteristics of the records show that the proposed method using step size until 4 times of the original record almost not change the original features of the earthquake records. Considering responses of the building shows that using large time steps cannot significantly change the base shear and displacement responses of the building but may strongly affect the acceleration responses, which is excited by eliminating higher modes of the building. On the other hand, the new method can significantly reduce the computational cost and used memory.

These results are related to the linear dynamic time history analysis of a 3-dimensional steel structure due to more than one component earthquake records. However, these results may be changed if different parameters are included, like material and/or geometric nonlinearities, P-delta effect, using different numerical method with other convergence speed, structure with complex modes, closeness of the modal characteristics, and finally parameters of earthquake records especially include intense changes during short times.

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REFERENCES

[1] M. Paz, *Structural Dynamics, Theory and Computation, 3rd Edition*, Van Nostrand Reinhold, New York, 1991.

[2] A. Soroushian, A technique for time integration analysis with steps larger than the excitation steps. *Communications in Numerical Methods in Engineering*, **24**: 2087-2111, 2008.

[3] **A.** Soroushian, On the performance of a conventional accuracy controlling method applied to linear and nonlinear structural dynamics. *Proceedings of the 17th International Congress on Sound & Vibration*, ICSV 17, Cairo, July 2010.

[4] http://www.BHRC.ac.ir/

[5] *Iranian Code of Practice for Seismic Resistant Design of buildings.* Standard No. 2800, 3rd ed., Building and Housing Research Center, Tehran, Iran, 2005.

[6] *Iranian National Building Code, Part 6: Structural Loadings.* Ministry of Housing and Urban Development, Tehran, Iran, 2004.

[7] *Iranian National Building Code Part 10: Steel Structures.* Ministry of Housing and Urban Development, Tehran, Iran, 2006.