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Investigation of strong-motion duration consistency in endurance time excitation functions

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Strong-motion duration;
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Damage indices.

Abstract. The Endurance Time (ET) method is a dynamic analysis procedure using intensifying excitation. The ET excitation functions are generated so that structural performance can be assessed at different excitation levels in a single response history analysis. ET accelerograms, which have been generated so far, possess response spectra consistency; this means that the duration consistency has not been directly considered. Strong-motion duration can influence the response of structures which have stiffness or strength degrading characteristics. In this paper, several well-known strong-motion duration definitions are studied in the context of the ET method. Ground motions are scaled to spectral acceleration of the code spectrum as well as the ET records; furthermore, the ET records are scaled to have consistent duration compared to real ground motion, considering different strong-motion duration definitions. In order to determine which definitions have the highest correlation with structure responses, several SDOF structures that have cyclic deteriorating behavior in stiffness and strength are subjected to both ET records and real ground motions. Since maximum inter story drift and maximum displacement of a structure subjected to several motions with roughly the same acceleration spectra but different motion durations are approximately identical, in this paper, the aim is to pursue the influence of motion duration in responses. Those indices which are based on energy and accumulative damage are employed. Correlation of each definition with structure responses has been examined by comparing the results of the ET records and real ground motion. Good performance of the ET records in a nonlinear region can be deduced due to the high correlation between the results of ET records and real ground motion. This paper provides an approach for considering the duration consistency in ET accelerograms. The efficiency of this approach for current ET accelerograms is also investigated.

1. Introduction

Earthquake motion should be characterized not only by using parameters related primarily to the amplitude of shaking, but also by the number of cycles and strong-motion duration which could play an important role in the response of structures. There are many studies investigating the correlation between structural responses and parameter related to strong motion duration. Their conclusions differ profoundly with respect to the influence of strong motion duration on structural response. In their studies, Hancock and Bommer [1] have concluded that duration is a secondary parameter, and exploration for a direct correlation between duration and damage is not practical. In fact, strong motion duration affects various types of damage indices in a different manner. Predominantly, damage indices related to cumulative energy and accumulated damage, such as absorbed hysteretic energy and fatigue, have a positive correlation with strong-motion duration,

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whereas damage indices related to maximum response, such as maximum inter story drift, do not have such a strong correlation. Moreover, Hancock and Bommer [2] have asserted that this phenomenon is further dependent on which dynamic property for the considered structure is used. On the other hand, until the structures subjected to earthquake motion do not exhibit nonlinear behavior, the influence of strong motion duration in response is negligible. Therefore, in order to investigate the influence of strong motion duration, nonlinear behavior should be included in the model of the structures. Consequently, a structure which has strength and stiffness degrading characteristics is more susceptible to the number of cycles of motion and, thus, strong-motion duration [2]. Despite the fact that more than 40 definitions for strong-motion duration have been proposed by different researchers, there is no universally accepted approach for its determination. Some of these definitions will be explained later in section 4. Consequently, this problem has been an obstacle for engineers when using strong-motion duration as criteria for their records selection. However, modern seismic codes, such as ASCE standards, propose that the duration of selected records shall be representative of the expected ground motion at the site for a given level of seismic hazard level.

In earthquake engineering, dynamic analysis is recognized as a method which could incorporate nearly all kinds of material and geometry in a more realistic manner, compared to other methods used for structural analysis. As a result of these advantages, the tendency to apply dynamic analysis is increasing more rapidly compared to the past; however, there are still a number of obstacles that prevent the prevailing use of this method. The endurance time method is a dynamic analysis procedure using specially designed intensifying accelerograms. In this methodology, the accuracy of the applied accelerograms is the predominant parameter which appreciably affects the results analysis. These accelerograms are generated so that they match the target spectrum (such as code spectrum) at a certain time, called target time and remain proportional to the code spectrum at all other times. In addition to amplitude parameters, strong ground motion parameters should be considered in the generation process of these accelerograms as well. The influence of motion duration has been investigated considering an equivalent number of cycles so far [3]. In this paper, this influence is investigated by strong motion duration. The question that remains is which strong-motion definition is the most useful indicator of the shaking characteristics of earthquake motion. This study determines which one of the existing strong-motion duration definitions has the most correlation with structural damage, considering the ET analysis concepts.

2. Ground motion selection

Non-linear dynamic analysis is becoming a popular procedure for seismic assessment of structure responses. Whenever this procedure is employed, the selection of ground motion as dynamic loading is a momentous consideration, because it can strongly influence the response of structures. The current design code for record selection is considered rather simplified compared to the potential influence of the selection process in dynamic analysis. Most contemporary seismic codes, such as ASCE standards 7-05 [4], describe relatively similar procedures for selection of the seismic input motion to be used as dynamic loading in structures. Seismic motion can be represented by real or simulated records, while several important seismological parameters, such as magnitude, distance, and local site conditions, should reflect the local seismic scenario [5]. Whenever a set of accelerograms are selected on the basis of criteria such as Magnitude-distance (M-R) pairs, a significant variability of the calculated response is found. This issue is attributed to neglecting other momentous parameters that should be used to characterize ground motion [6].

In this study, the record set proposed by the FEMAp695 code for the collapse assessment of a building structure is used [7]. The aforementioned record selection procedures are mainly dependent on seismological conditions, whereas the FEMAp695's record set is selected so that their records can be applied to structures located at different sites with a variety of ground motion hazard function, site and source conditions. Consequently, a set of twenty two ground motions are used that belong to bin of relatively large magnitudes of 6.5-7.6, which are proposed in FEMAp695 as the far-field set. The acceleration spectra of these records are depicted in Figure 1.

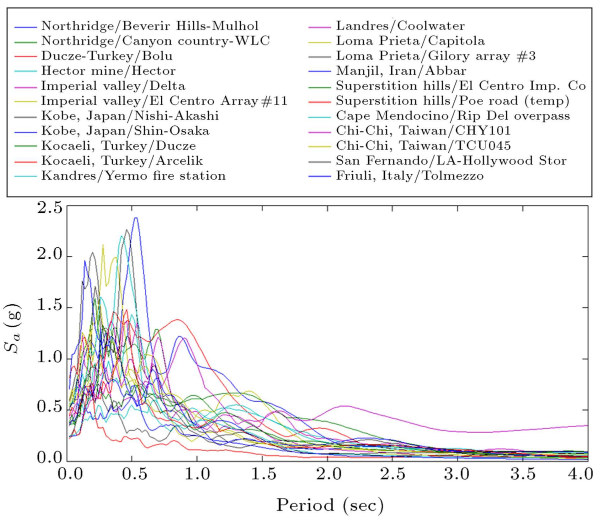

Figure 1. Acceleration spectra of employed records associated with FEMAp695.

3. ET excitation functions

ET accelerograms are intensifying motions which should make meaningful correspondence between the response of a structure at a particular time in ET analysis and the average of the response to ground motions [8]. These ground motions should represent the seismicity of a particular site at a certain hazard level. Generally, the spectrum of ET excitation functions at all times can be attributed to the spectrum associated with a particular hazard level. In order to reduce the complexity of this problem, the spectrum of the ET accelerogram is matched only at one particular time to a target spectrum. This particular time is called the target time. The target spectrum can be a code spectrum such as the Iranian National Building Code (2800. Code) [9] or the average spectrum of several ground motions. For other times, the produced spectrum by the ET accelerograms varies linearly as:

$$S_{aC}(T,t)\frac{t}{t_{\text{target}}}S_{aC}(T), \tag{1}$$

where $S_{aC}(T)$ is the target spectrum, $S_{aC}(T,t)$ is the spectrum to be produced at time (t) by ET excitation functions, and t_{target} is target time.

Furthermore, the displacement spectrum is a highly important consideration in characterizing a dynamic excitation. The target displacement spectrum can be defined as a function of the acceleration spectrum as:

$$S_{uC}(T,t)=\frac{t}{t_{\text{target}}}S_{aC}(T)\times\frac{T^2}{4\pi^2}, \tag{2}$$

where $S_{uC}(T,t)$ is the target displacement spectrum to be induced at time (t) by the ET excitation functions.

In the ETA20e series of ET accelerograms, the average of the spectrum of a suite of ground motions is used as the template spectrum. The acceleration spectra and the name of these ground motions is displayed in Figure 2.

In Figure 3, the ETA20e01 excitation function is shown. The trend of intensifying motion can be seen in Figure 3.

The suitability of the ETA20e series of ET accelerogram, in producing the template spectrum at the target time, and the linearly varying acceleration spectrum at other times, is investigated schematically in Figure 4.

The basic concepts of the method were published in 2004 [10]. In the second generation of ET accelerograms, the concept of response spectrum and numerical optimization were introduced, and suitable accelerograms were numerically generated [11]. These accelerograms are considered suitable because they can be used to predict the response of structures in a more precise manner. By extending the range of vibration period into very long periods, the records in this generation further produced highly reasonable estimates in the non-linear range of behavior [12]. Non-linear analysis of SDOF systems considering different material models was published in 2009 [13]. In the third generation, non-linear response spectra were included in the optimization procedure [14]. The procedure has recently been extended for multi-component analysis [15].

This study uses four series of ET accelerograms, which are presented in Table 1.

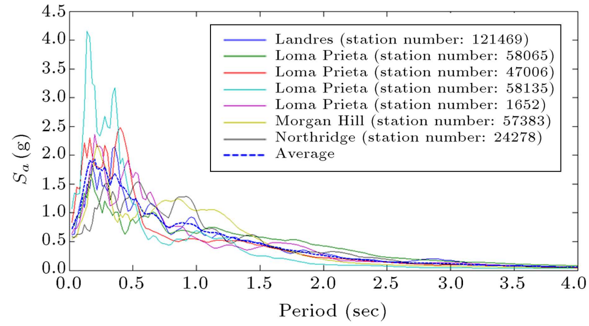

Figure 2. Acceleration spectra of ground motions used to generate ETA20e series.

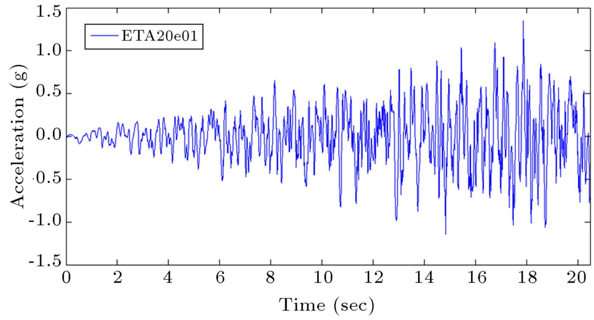

Figure 3. ETA20e01 excitation function.

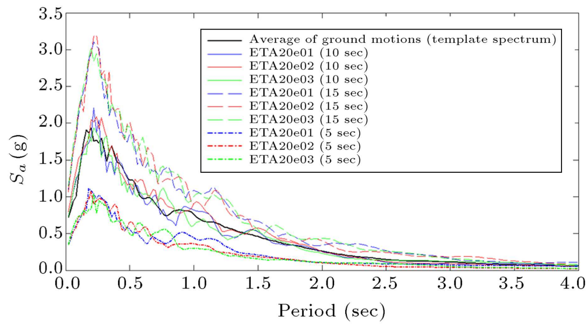

Figure 4. Acceleration spectrum produced by ETA20 series of ET accelerograms at different times.

Table 1. Characteristics of used ET accelerograms.

Series	Target spectrum	Inclusion long period	Non-linear optimization
ETA20a	Code spectrum(standard 2800)	N	N
ETA20e	Average of several recorded motion on stiff soil	Y	N
ETA40g	Code spectrum(ASCE standard)	Y	N
ETA20en	Average of several recorded motion on stiff soil	-	Y

4. Review of definitions of strong-motion duration

All strong-motion duration definitions can be classified into three generic groups, including: Bracketed-Duration, Uniform-Duration, and Significant-Duration. The "Bracketed Duration", D_b, is defined as the total time of motion which elapsed between the first and last extrusion of a specified level of acceleration, a_0, [16] as schematically for an accelerogram using a threshold of 0.05 g, depicted in Figure 5.

One of disadvantage of this definition is that it only considers the first and last excursion of the specified threshold and completely ignores the characteristics of the strong shaking phase, which can result in a long duration for earthquakes with a small sub-event occurring after the main shock has passed.

The second group is "Uniform durations", D_U, which are defined as the sum of time intervals during which the acceleration is greater than the specified threshold [16], as illustrated in Figure 6.

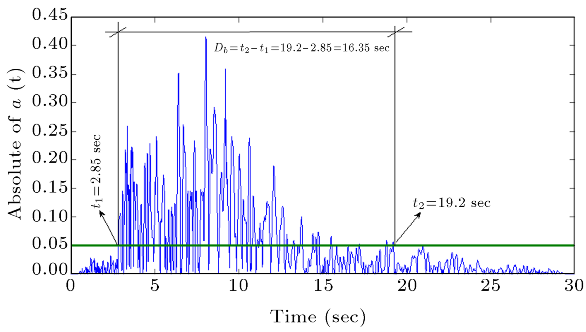

Figure 5. "Bracketed duration" of an accelerogram.

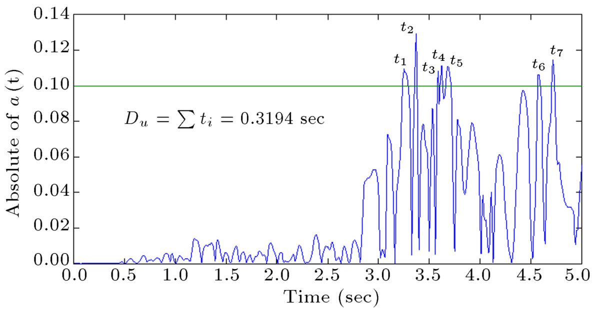

Figure 6. "Uniform Duration" of an accelerogram.

This definition has the disadvantage that it does not define a continuous time window, during which the shaking can be considered strong and used as the input motion of dynamic analysis.

The third group is called "Significant Duration", D_s, and this is based on the accumulation of energy in an accelerogram, represented by the integral of the square of the ground acceleration, velocity and displacement. If the integral of the square of ground acceleration is employed, the quantity is related to the Arias intensity, AI [17].

$$\mathrm{AI} = \frac{\pi}{2g} \int_0^{t_r} a^2(t)dt, \tag{3}$$

where t_r is assigned as the total duration of the accelerogram, a (t) is the acceleration time-history and g is the acceleration due to gravity. The "Significant Duration" is defined as the time interval over which some specified proportion of the total energy is accumulated [16]. This approach for limits of 10% to 90% of the total energy for an accelerogram is illustrated on a plot of the build-up of Arias intensity, in Figure 7.

The root-mean-square of an accelerogram is defined as [16]:

$$a_{rms} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a^2(t)dt, \tag{4}$$

where t_1 and t_2 are the beginning and end of the time interval under consideration, respectively. Any definition based on the root-mean-square of an accelerogram is categorized into "Significant Duration" [16].

The concept of "Significant Duration" has the advantage that it considers the characteristics of all accelerograms and defines a continuous time window, during which the motion can be considered strong.

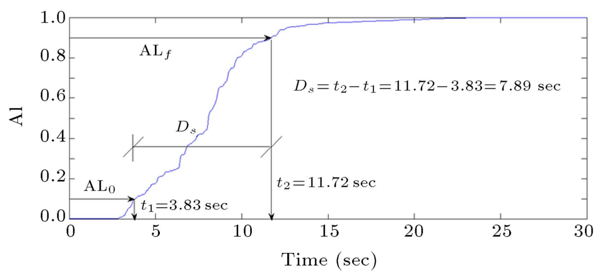

Figure 7. "Significant Duration" of an accelerogram.

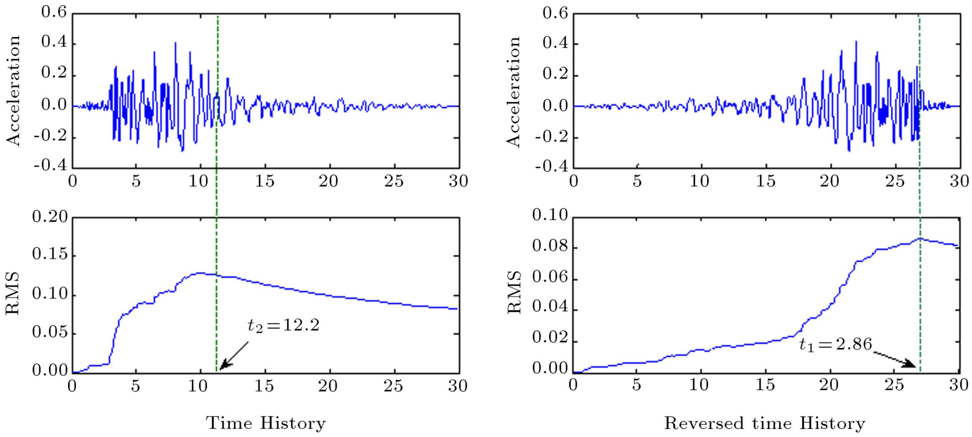

Figure 8. Definition of strong-motion duration by McCann and Shah [18].

McCann and Shah [18] have defined strong-motion duration by plotting the cumulative a_{rms} of the accelerogram, noting that beyond a certain point, it begins to decay. The end of the strong motion phase is determined by plotting the derivate of the cumulative a_{rms} function against time and noting that the time beyond remains negative [19]. The start of the strong motion phase is determined in exactly the same way by using the reverse acceleration time-history [16]. This procedure is depicted in Figure 8.

5. Comparison between ET accelerograms and ground motion

The strong-motion duration of both ET records and ground motion using different duration definitions is calculated. For ground motion, the average duration of motion is under consideration, as seen in Figure 9 in the dashed line. The ET records at each time window can be considered as a single motion; for instance, 10 or 20 sec windows of an ET record are two separate motions. Therefore, an ET record inherently is not a single motion and, hence, its strong-motion duration is varied against time. As shown in Figure 9, the duration of ETA20a01, ETA20a02 and ETA20a03 (three accelerograms of ETA20a series) is calculated at each time. It is noteworthy that unlike the significant

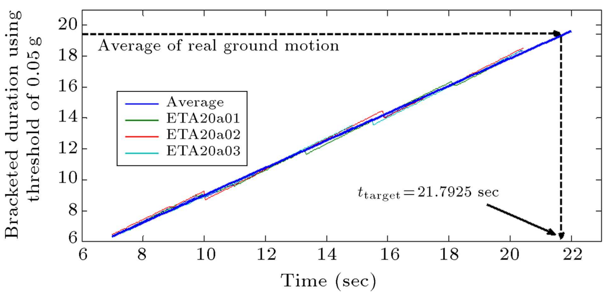

Figure 9. Procedure to determine the target time.

duration, bracketed duration and uniform duration depend on how the record is scaled. In this study, the ET records and real ground motion are scaled so that they produce EPA equal to 0.35 g. For ET records, a scaling process is performed for each window. Afterwards, the target time is identified as the times at which the motion duration of the ET records will be equal to the ones associated with real ground motion. The target time is determined schematically and presented in Figure 9.

A similar procedure is performed for other series of the ET records and different strong-motion duration definitions. The target times associated with different series of ET accelerograms and different strong-motion definitions are presented in Table 2. Dispersion of the results is evident. For instance, the target time for ETA20a using bracketed duration with a threshold of 0.05 g is 25.29 sec; however, ETA20en using significant duration with limits of 5% and 75% is 9.68 sec.

6. Evaluation of proposed target time

In order to evaluate the effectiveness of each target time presented in Table 2, several degrading models with different periods and different ductility ratios are constructed and then subjected to both ET records and real ground motion. It should be noted that the ET records are scaled to the proposed target times, which are computed using different strong-motion definitions. In this study, the peak-oriented model is employed to characterize the hysteretic behavior of materials. This model keeps the basic hysteretic rules proposed by Clough and Johnston [20] and later modified by Mahin and Bertero [21], but the backbone curve is modified to include strength capping and residual strength [20]. A basic rule for the peak-oriented hysteretic model is illustrated in Figure 10.

Moreover, the damage index proposed by Kunnath and Jenne [22] is considered a damage indicator

Table 2. Target time for different series of ET accelerograms.

	Target time						
Series	D_b **(0.05 g)***	D_b **(0.1 g)**	D_u **(0.05 g)**	D_u **(0.1 g)**	**RMS**	D_s **(5-75%)**	D_s **(5-95%)**
ETA20a	25.29	14.64	11.12	3.84	22.49	9.63	19.11
ETA20e	27.09	15.65	12.84	4.52	23.41	9.81	20.56
ETA40g	26.61	15.29	13.03	4.00	22.59	9.53	20.54
ETA20en	28.08	15.35	13.17	4.13	22.69	9.68	20.51

* Quantity in the parenthesis indicates the thresholds used in the duration definitions.

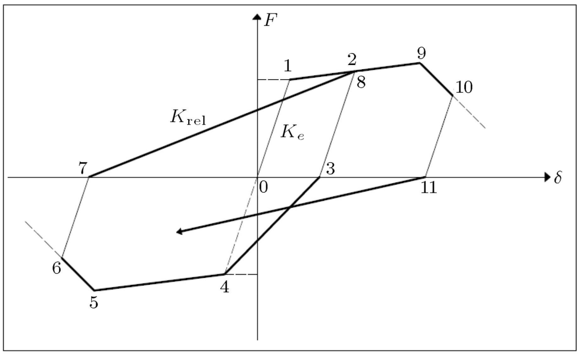

Figure 10. Peak-oriented hysteretic model that is used to characterize the nonlinear behavior of SDOF structures [19].

in this study. In the Park-Ang damage index, damage is expressed as a linear combination of maximum deformation and the effect of repeated cyclic loading [23]. Kunnath and Jenne modified the Park-Ang damage index as [22]:

$$\overline{D}^K_{PK} = \frac{\mu_{\theta m} - \mu_{\theta y}}{\mu_{\theta u} - \mu_{\theta y}} + \overline{\beta_K}\frac{E_{hm}}{M_y \mu_{\theta u}\theta_y}, \tag{5}$$

where $\mu_{\theta u}$ is the ultimate rotation ductility under a monotonic static load. Parameters used for characterizing the hysteretic behavior of the material are $\alpha_1 = 0.1$, $\alpha_2 = -0.03$, $\frac{\theta_c}{\theta_y} = 11$, $\mu_{\theta u} = 8$, $\overline{\beta_K} = 0.15$ where α_1, α_2 are post yielding stiffness and post capping stiffness ratios, respectively. The high value of $\overline{\beta_K}$ used in this study implies the higher contribution of hysteretic energy dissipation to damage. The latter statement guarantees that the used damage index accounts for the duration of strong motion and cumulative inelastic action. These SDOF structures are chosen to have periods of 0.2 to 3 sec and ductility of 2 to 6. It is assumed that these SDOF structures can be representative of all typical structures based on their period and nonlinear behavior.

Afterwards, the designed structures are subjected to both ET records and real ground motion. Both the ET records and real ground motion are scaled. The scaling process of ground motion records only considers the spectral value at the period of structures. On the other hand, the scaling process of ET records further considers the time at which the ET records should reach the target spectrum, called the target time. In this study, the target time of ET records considering different strong-motion definitions is determined, so that the ET records have consistent duration compared to real ground motion.

For comparative purposes, the damage indices of structures when subjected to ET records are plotted versus those when subjected to real ground motion. Moreover, for the quantitative comparison of each proposed target time, the δ parameter is defined as:

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{DI_{\rm RG} - DI_{\rm ET}}{DI_{\rm RG}}\right)^2}, \tag{6}$$

where $DI_{\rm RG}$ and $DI_{\rm ET}$ are damage indices of the structure when they are subjected to real ground motion and ET records, respectively. N is the number of structures which are considered in this study. Table 3 represents this value for different motion duration definitions and different series of ET accelerograms. In addition, the linear correlation factor for data is calculated. Table 4 represents this value for different series of ET accelerograms and different motion duration definitions. Figure 11 shows a high correlation between results of the ET accelerograms and real ground motion.

Table 3 displays a more effective scaling process for each series of ET accelerogram; for instance, scaling

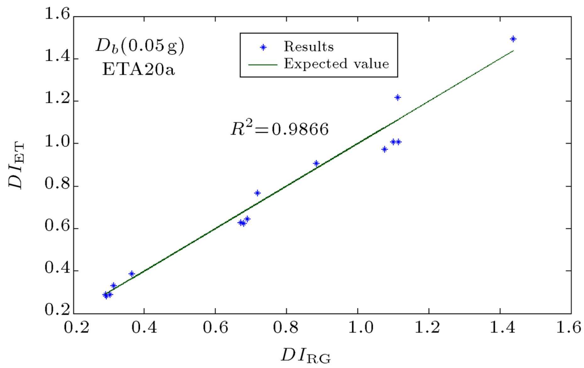

Figure 11. Revelation of correlation between the results of ET records and real ground motions.

Table 3. δ value for different series of ET accelerograms and different strong motion definitions.

	δ value						
Series	D_b **(0.05 g)**	D_b **(0.1 g)**	D_u **(0.05 g)**	D_u **(0.1 g)**	**RMS**	D_s **(5-75%)**	D_s **(5-95%)**
ETA20a	-	0.017	0.030	0.059	-	0.030	0.019
ETA20e	-	0.035	0.229	0.300	-	0.011	0.957
ETA40g	0.049	0.027	0.019	0.034	0.038	0.022	0.048
ETA20en	-	0.030	0.275	0.507	-	0.026	0.906

(-) line indicates that the mentioned value couldn't be calculated because there is no record with that duration.

Table 4. Linear correlation factor for different series of ET accelerograms and different strong motion definitions.

	R^2						
Series	D_b **(0.05 g)**	D_b **(0.1 g)**	D_u **(0.05 g)**	D_u **(0.1 g)**	**RMS**	D_s **(5-75%)**	D_s **(5-95%)**
ETA20a	-	0.987	0.998	0.976	-	0.993	0.990
ETA20e	-	0.991	0.992	0.995	-	0.996	0.943
ETA40g	0.981	0.975	0.990	0.995	0.978	0.997	0.962
ETA20en	-	0.992	0.991	0.992	-	0.975	0.962

Table 5. Ranking of different series of ET accelerogram considering different criteria.

Series	**Best indicator**	**Target time**	**Lowest delta**	**Rank of lowest delta**	**Rank of highest** R^2
ETA20a	D_b (0.1 g)	14.64	0.017	2	1
ETA20e	D_s (5-75%)	9.81	0.011	1	3
ETA40g	D_u (0.05 g)	13.03	0.019	3	2
ETA20en	D_s (5-75%)	9.68	0.026	4	4

based on Bracketed-Duration with a threshold of 0.1 g will be more rewarding for ETA20a. Table 4 shows the high correlation between results of ET accelerograms and real ground motion. Table 5 summarized all conclusions from Tables 3 and 4. As can be seen in Table 5, for each series of ET accelerogram, the best indicator of the influence of motion duration is introduced, for instance for the ETA20a series, the bracketed duration with a threshold of 0.1 g is the best duration definition, and 14.64 is the best target time that makes the best duration consistency between ET accelerograms and ground motion. The best series of ET accelerograms is also determined. ETA20e is the best series of accelerograms, considering the high precision of results derived when this series was employed.

7. Conclusions

In this study, the significance of strong-motion duration in ET analysis has been investigated. As a result of this study, the following can be concluded:

1. Duration of motion does not differ widely for different series of ET accelerograms. It means that the duration of current ET accelerograms is not sensitive to the target spectrum used to generate them.
2. The scaling process which is more effective in making the best level of compatibility between ET records and ground motions, is not the same for different series of ET accelerogram; therefore, a single procedure for scaling ET accelerograms that is well consistent with real motion cannot be prescribed.
3. The optimum target time, which makes the best consistency between ET accelerograms and ground motions, differs for different series of ET accelerograms. It reveals that specifying a particular target time cannot guarantee the best level of consistency in considered records.
4. High correlation between the results of ET accelerograms and ground motions reveals the acceptable performance of the ET records in a nonlinear region. Contrary to what was expected, the ETA20e series of ET accelerograms that are modified in a nonlinear region show, relatively, the weakest correlation between the different series of ET accelerograms.
5. As expected, the response of structures subjected to ETA20a series, ETA20e series, and ETA40g series, which have a similar generation approach

but a different target spectrum, will be different, due to the contribution of spectral values at longer periods. The ETA20e series of ET accelerograms are matched to the average spectrum of recorded motion on stiff soil. This similarity between spectral acceleration of the ET records and ground motions makes the ETA20e series more compatible compared to others in this regard.

Acknowledgment

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Nomenclature

AI	Arias Intensity
$a(t)$	Acceleration time history
D_b	Bracketed duration
D_U	Uniform duration
D_s	Significant duration
DI_{ET}	Damage indices when they are subjected to real ET records
DI_{RG}	Damage indices of structure subjected to real ground motion
$\overline{D}_{PK}^{K}$	Damage Index
g	Acceleration due to the gravity
N	Number of structures considered in this study
$S_{aC}(T)$	Target spectrum
$S_{aC}(T,t)$	Acceleration spectrum to be induced at time t
$S_{uC}(T,t)$	Target displacement spectrum at time t
T	Free vibration period
t	Time
t_r	Total duration of an accelerogram
t_1	Beginning of interval
t_2	End of interval
α_1	Post yielding stiffness ratio
α_2	Post capping stiffness ratio
$\overline{\beta_K}$	Constant parameter in damage index formula
δ	Comparative parameter
$\mu_{\theta u}$	Ultimate rotation ductility under a monotonic static load
$\mu_{\theta m}$	Maximum rotation ductility
$\mu_{\theta y}$	Yield rotation ductility

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