

Characteristics of Second Generation Endurance Time Acceleration Functions

V. Valamanesh¹, H.E. Estekanchi^{1,*} and A. Vafai¹

Abstract. *The Endurance Time (ET) method is a time-history based dynamic pushover procedure in which structures are subjected to specially designed, intensifying accelerograms, and their seismic performance is judged based on the time duration needed to satisfy the required design objective. Second generation refers to ET acceleration functions that are generated by application of optimization techniques in order to produce response spectra compliant linearly intensifying accelerograms. In this paper, the major characteristics of a set of second generation ET acceleration functions (ETA20a01-3) are investigated. The template response spectra of this set of ET acceleration functions corresponds to the design spectra of the Iranian National Building Code (Standard 2800) for stiff soil (type II). Results show that a good correspondence can be established between the effective ground motion parameters of earthquakes and ET acceleration functions at specific target times. Therefore, it is expected that ET acceleration functions can be used to predict various demand parameters of structures subjected to ground motions whose response spectra is more or less compatible with the adopted template response spectra. Discrepancies between characteristics of ET acceleration functions and ground motions have also been discussed.*

Keywords: *Dynamic pushover; Intensifying acceleration functions; Endurance time method.*

INTRODUCTION

In recent years, advanced analysis procedures have been proposed in order to reliably predict the actual behavior of complex structures subjected to strong earthquakes. Time-history based procedures are becoming more popular among researchers, due to the fact that in these procedures, nearly all sorts of complicated material and geometry can be directly included in the analysis. In other words, model complexity is not considered an obstacle in time-history analysis, at least at the theoretical level. However, intensive computational demand has prohibited the widespread use of such analyses in design offices, and simplified procedures are still needed in practice.

The Endurance Time (ET) method is an alternative time-history based dynamic pushover procedure that has a good potential for utilization in practical [1].

In ET method, structures are subjected to specially designed, intensifying accelerograms called “ET acceleration functions”, in a manner where the re-

sponse spectra of such acceleration functions linearly increase by time, and their seismic performance is judged based on the time interval for the duration of which they can endure the imposed dynamic excitation [2]. The criteria in measuring endurance time can be selected based on the problem to be the value of basic design parameters such as maximum drift or displacement, maximum stress ratio or any other desired parameter or damage. Since the excitation imposed on the structure is an increasing function with time, the maximum value of displacements, internal forces and other response parameters also increase with time in ET analysis.

In this paper, some basic properties of ET acceleration functions that can be interesting from the seismic assessment viewpoint have been studied. The observation of damages in buildings after severe earthquakes shows strong interdependency between some ground motion parameters and the structural response. Because of the complexity of earthquake ground motions, identification of a single parameter that accurately describes all important ground motion characteristics is regarded as impossible [3].

It is found that spectral acceleration (S_a) and spectral absolute seismic input energy have the strongest correlation with the overall structural dam-

1. Department of Civil Engineering, Sharif University of Technology, Tehran, P.O. Box 11155-9313, Iran.

*. Corresponding author. E-mail: stekanchi@sharif.edu

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age indices. On the other hand, the PGA, CP (Central Period, defined as the reciprocal value of the number of positive zero-crossing per time unit of the seismic acceleration) and SMD (Strong Motion Duration) exhibit poor correlation with the overall structural damage indices [1].

This paper includes a preview of major characteristics of the first set of second generation ET acceleration functions. The term ‘first generation’ refers to those ET acceleration functions that were generated by using a heuristic approach and applying a linearly increasing profile curve directly to a filtered acceleration function without direct control over response parameters. The term ‘second generation’ refers to those acceleration functions in which optimization procedures have been applied in order to produce linearly proportional spectrum compliant acceleration functions. These acceleration functions make use of typical, codified design spectra as a template spectrum [4,5]. The results presented in this paper are aimed at providing a better understanding of various characteristics of these ET acceleration functions and preparing a reference for clearer interpretation of ET analysis results reported in other literature.

GENERATION OF ET ACCELERATION FUNCTIONS

In the first generation of ET acceleration functions, the process of generating the acceleration functions started from a random vibration accelerogram similar to a white noise which was modified by a filter in the frequency domain and then made compliant with a typical code design response spectrum. The resulting stationary accelerogram was then modified by applying a linear profile function that made it intensify with respect to peak accelerations at different time intervals. These accelerograms served well the purpose of demonstrating the concept of ET analysis, but could not be expected to result in quantitatively significant results.

In this paper, the second generation of ET accelerograms has been used. In this generation of ET accelerograms, in order for the ET acceleration functions to somehow correspond to average code compliant design level earthquakes, the concept of the response spectrum has been more directly involved. As will be explained later, these ET acceleration functions are designed in such a way to produce dynamic responses equal to the code’s design spectrum at a predefined time, t_{Target} , and therefore it is possible to compare the performance of different structures with different periods of free vibration. The time plot of a typical ET acceleration function produced by the mentioned procedure has been depicted in Figure 1.

To calculate the response spectrum of an ET

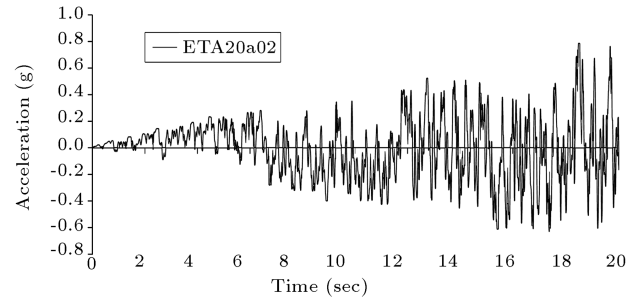


Figure 1. ETA20a03 acceleration function.

acceleration function at each time, e.g. t_1 , the ET acceleration function is cut at t_1 , and its response spectrum is sketched versus the period of vibration. By this approach, the average of the response spectra of three ET acceleration functions at $t = 5$ sec, $t = 10$ sec and $t = 15$ sec are depicted in Figure 2a. The target time for this set of ET acceleration functions has been set to 10 sec, therefore the response at $t = 10$ sec should match the codified value with a scale factor of 1.0. At $t = 5$ sec and $t = 15$ sec, the response spectra of these acceleration functions should match 0.5 and 1.5 times the standard codified values, respectively. As can be seen in Figure 2, the optimization process is quite successful in converging to the target values.

As expected, acceleration responses follow target values with almost the same level of dispersion as spectral acceleration.

COMPARISON OF ET RESPONSE SPECTRUM WITH REAL EARTHQUAKE

Even though ET acceleration functions are fundamentally different from earthquake records, it still helps to compare the level of various excitation parameters at different times with some real earthquake records set as some sort of bench-mark. The acceleration response

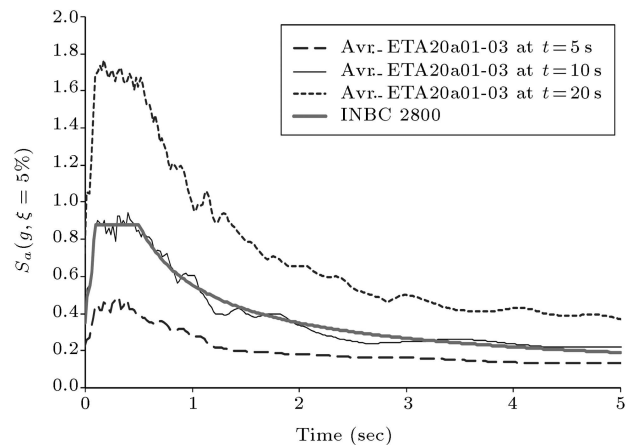


Figure 2. Average response spectra of ETA20a acceleration functions for $\xi = 5\%$ at different time.

spectrum is one of the most significant parameters from a structural engineering viewpoint.

As explained earlier, the template response spectra used in the generation of the ETA20a series of accelerograms, is that of the Iranian National Building Code (INBC) for stiff soil (type II). To compare this response spectrum with ground motions, the response spectra of 7 earthquakes recorded on soil type C, according to NEHRP provisions, listed in Table 1, are sketched in Figure 3. It should be noted that the characteristics of site class C of NEHRP are very similar to soil type II of the INBC.

It is evident that at short periods, the ET response spectrum conforms to the INBC code, as well as the average response spectrum of ground motions. However, at long periods ($T > 0.4$ sec), the ET and INBC response spectra are considerably greater than the average of 7 ground motions. This is a result of the corrections to the codified design spectrum in the long period range and should be considered when comparing ground motions and code compliant accelerograms.

BASIC GROUND MOTION PROPERTIES

A quick look at the virtual ground velocity and displacement produced by ET records, as depicted

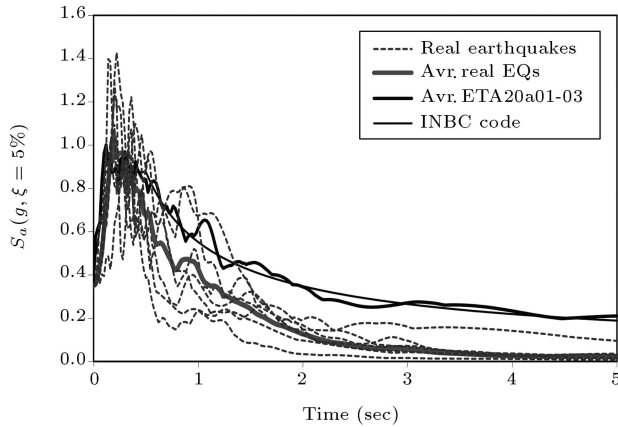


Figure 3. Comparison of ET response spectra ($t = 10$ sec), INBC code and earthquakes response spectra.

in Figure 4, reveals some essential differences. As can be seen in these figures, equivalent displacements and velocities produced by ET records become too high after about 4 to 5 seconds. It should be noted that while a ground displacement of about 90 m for ETA20a03 in Figure 4b cannot be compared to any real ground motion, it actually complies with the concepts of ET analysis and does not result in any discrepancies for linear structures with a period of free vibration of up to about 5 seconds, which can be considered quite a long period for most building structures.

As explained before, the ETA20a series of acceleration functions have been optimized to fit with INBC code design spectra for stiff soil in the linear range. An evident conclusion from Figure 4 is that this set of ET accelerograms cannot be expected to yield reasonable results for structures with periods higher than 5 seconds. This conclusion also applies to structures with highly nonlinear behavior where nonlinearity affects

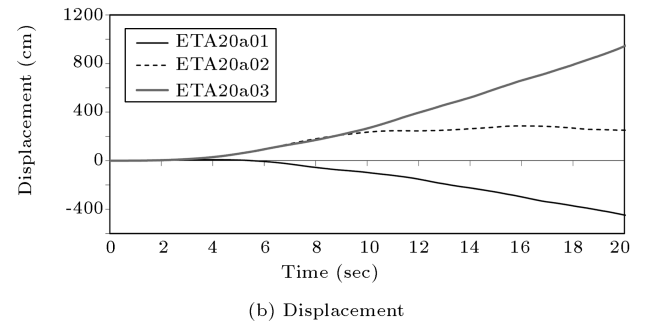
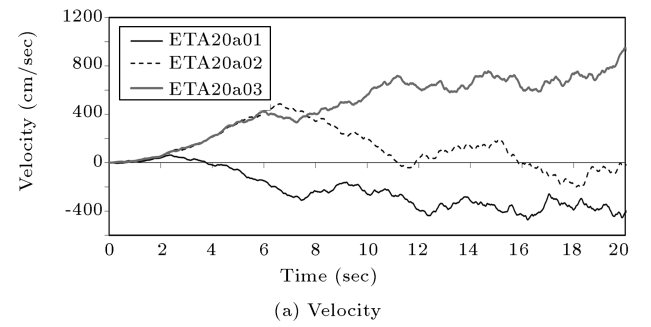


Figure 4. Velocity and displacement of ETA20a acceleration functions. a) Velocity, b) Displacement.

Table 1. Actual recorded events on soil condition C.

Earthquake Name	M_s	St Number	Abbreviation	PGA (cm/s^2)
Landers	7.5	12149	DSP000	167.80
Loma Prieta	7.1	58065	STG000	494.50
Loma Prieta	7.1	47006	GIL067	349.10
Loma Prieta	7.1	58135	LOB000	433.10
Loma Prieta	7.1	1652	AND270	239.40
Morgan Hill	6.1	57383	G06090	280.40
Northridge	6.8	24278	ORR360	504.20

the structure in such a way as to elongate its effective period of vibration. Also, in the range of periods below 5 seconds, displacement demands resulted from INBC design spectra are expected to be significantly higher than those from ground motions. Therefore, the ETA20a series of acceleration functions are not recommended for application in high period and highly nonlinear cases.

FREQUENCY CONTENT

Dynamic responses of structures are very sensitive to the frequency at which they are loaded. Earthquakes produce complicated loading with components of motion that span a broad range of frequencies. The frequency content describes how the amplitude of a ground motion is distributed among different frequencies.

The Fourier amplitude of ET acceleration functions up to 10 sec is depicted in Figure 5. It is obvious that the Fourier amplitude of ET acceleration functions decreases at higher frequencies, which for low frequencies is considerable and which for high frequencies becomes negligible.

Like response spectrum at frequencies between 2.5 and 10 Hz ($0.1 < T < 0.4$ sec), the Fourier amplitude of ET acceleration functions is the same as the average of ground motions. However, at long and short frequencies ($f < 2.5$ Hz and $f > 10$ Hz), the Fourier amplitude of ET acceleration functions is greater than the average of 7 earthquakes. An important note is that for almost all frequency ranges, the Fourier amplitude from ET acceleration functions is greater than that of ground motions. It should be mentioned that the frequency content of ET acceleration functions is indirectly modified during the optimization process, so that the response matches target values. As can be seen in Figure 5, the frequency content is reasonable in the

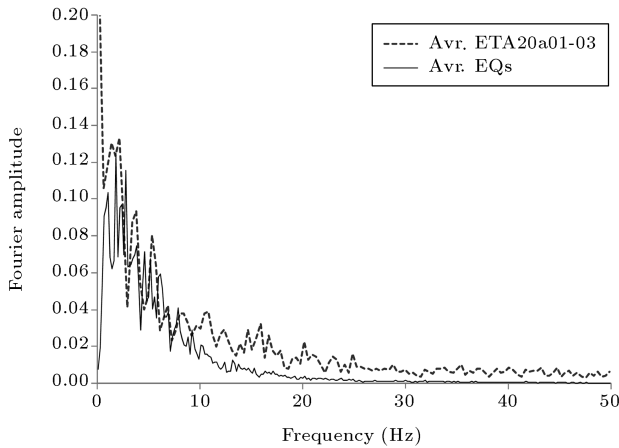


Figure 5. Comparison of frequency content between ET acceleration functions (at $t = 10$ sec) and ground motions.

practical range of about 2.5 to 10 Hz, where numerical optimization has been carried out. Outside this range, the discrepancy is high. Therefore, for situations where effective frequencies can be outside this range, appropriate ET acceleration functions covering relevant frequency ranges should be used.

POWER SPECTRAL DENSITY

ET acceleration functions are inherently non-stationary and their amplitude increases linearly by time. Therefore, a non-stationary approach should be used to describe the PSD of ET acceleration functions. The total intensity of the ground motion with duration T_d is calculated in the time domain by the following equation:

$$I_0 = \int_0^{T_d} [a(t)]^2 dt. \quad (1)$$

From Parseval's theorem, I_0 can also be expressed in the frequency domain as:

$$I_0 = \frac{1}{\pi} \int_0^{\omega_N} [c_n]^2 d\omega, \quad (2)$$

where $\omega_N = \pi/\Delta t$ is the Nyquist frequency and c_n is the Fourier amplitude at frequency ω_N .

Power Spectral Density (PSD) is defined such that:

$$G(\omega) = \frac{1}{\pi T_d} c_n^2. \quad (3)$$

The close relationship between the power spectral density function and the Fourier amplitude is apparent from this equation. The power spectral density is normalized by dividing its values by the area beneath it.

Results from the average of ET acceleration functions (Avr ETA20a01-3) and 7 ground motions are depicted in Figures 6 and 7. It is obvious that spectral density increases parabolically by time.

It is obvious from Figure 7 that ET acceleration functions are broadband, therefore, most structures with a wide range of vibration frequency could be affected by these acceleration functions.

In a frequency range between 2.5 Hz and 10 Hz, the average power spectral density of ET acceleration functions and actual records are similar, therefore the stochastic analysis of structures in those frequencies by ET acceleration functions and these ground motions may lead to the same results.

Stochastic analysis of structures with natural frequencies less than 2.5 Hz and higher than 10 Hz, by

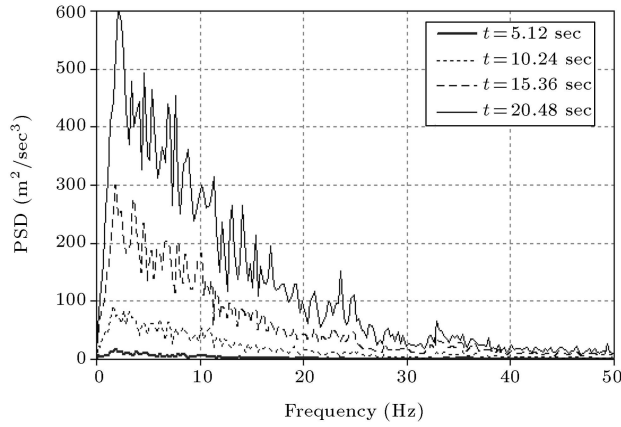


Figure 6. Power spectral density function for average of three ET acceleration functions, ETA20a01-03.

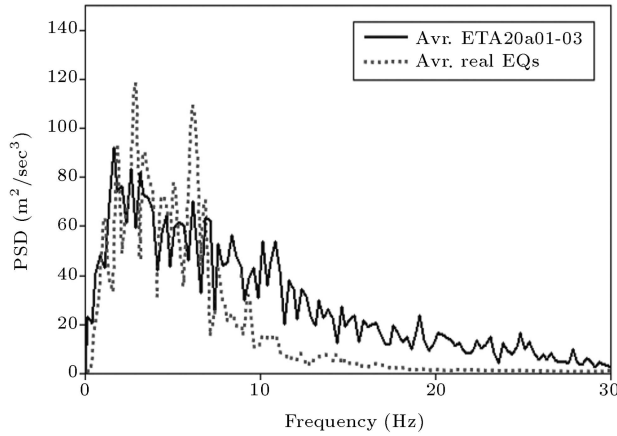


Figure 7. Comparison of power spectral density for average of 7 ground motions and average of ET acceleration functions at $t = 10$ sec.

the ET method, are more conservative compared to real accelerograms. However, they are similar for natural frequencies between 2.5 Hz and 10 Hz. Such differences are to be expected, because the design spectrum is not intended to match the response spectrum of any particular ground motion, but is constructed to represent the average characteristics of many ground motions with a margin of safety.

OTHER GROUND MOTION PARAMETERS

A number of ground motion parameters have been proposed to extract important information from each parameter.

Energy Parameters

The energy spectrum may be used to provide additional important information about the damage potential of earthquake ground motion related to these cumulative effects.

Figure 8 illustrates the energy spectra for ET acceleration functions at $t = 10$ sec and ground motions.

It is obvious that the input energy for ET acceleration function at $t = 10$ sec does not conform to real accelerograms, especially at higher periods, and is remarkably greater than that of ground motions.

Specific Energy Density (SED) is defined as:

$$\text{SED} = \int_0^{T_d} [\dot{v}_g(\tau)]^2 d\tau, \quad (4)$$

where \dot{v}_g is the ground motion velocity and T_d is the duration of the earthquake. The SEDs of records are illustrated in Figure 9.

It is obvious that the SED of ET acceleration functions is remarkably greater than the average of earthquakes in such a way that the SED of ET acceleration functions reaches an average amount for selected ground motions at 2 seconds.

Intensity Parameters

Arias intensity (I_a) is closely related to the root mean square of acceleration, and is useful to characterize the frequency content and power spectral density of

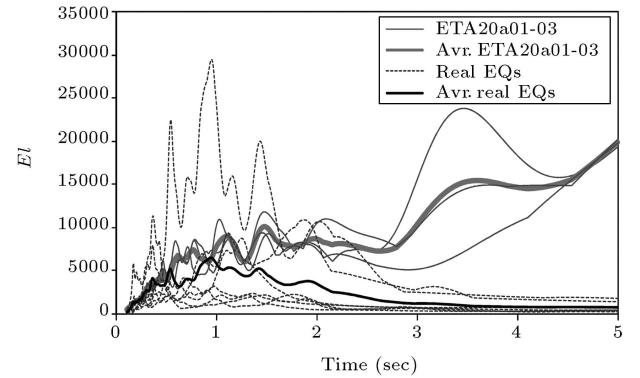


Figure 8. Comparison of energy spectra between ET acceleration functions at $t = 10$ sec and ground motions.

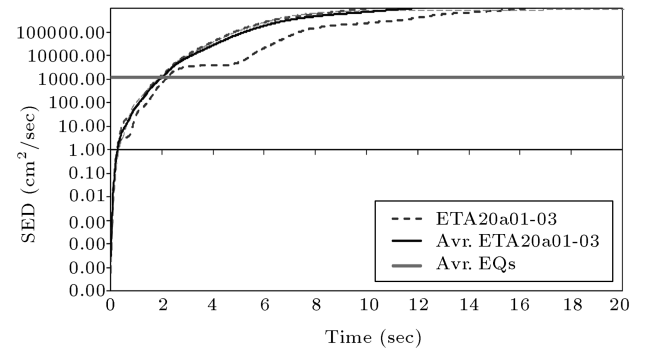


Figure 9. Comparison of SED between ET acceleration functions and ground motions.

accelerograms:

$$I_a = \frac{\pi}{2g} \int_0^{T_d} [a_g(t)]^2 dt. \quad (5)$$

The characteristic intensity, I_c , is linearly related to an index of structural damage due to maximum deformations and absorbed hysteretic energy.

$$I_c = (a_{rms})^{3/2} \sqrt{T_d}. \quad (6)$$

A95 is defined as the level of acceleration that contains up to 95 percent of the Arias Intensity [6].

Acceleration Spectrum Intensity (ASI) and Velocity Spectrum Intensity (VSI) are defined as:

$$ASI = \int_{0.1}^{0.5} S_a(\xi = 0.05, T) dT, \quad (7)$$

$$VSI = \int_{0.1}^{2.5} S_v(\xi = 0.05, T) dT. \quad (8)$$

The above parameters are calculated for ET acceleration functions and compared with the average of seven earthquakes. Results are depicted in Figure 10 through Figure 14.

As can be seen in Figure 10, the Arias intensity parameter for ETA20a acceleration functions matches the average of selected ground motions at about $t = 8$ sec, and increases with a hyperbolic trend with time.

As can be seen in Figure 11, a A95 parameter is a nearly linear function of time and matches the average of selected earthquakes at about $t = 9$ sec. Also, from Figure 12, the parameter, I_c , of the average of ground motions is equal to that of ET acceleration functions at $t = 6$ sec.

Acceleration and velocity spectrum intensities are depicted and compared with ground motions in Figures 13 and 14.

It is evident from these figures that these two parameters linearly increase and match the average of ground motions at about $t = 8$ sec.

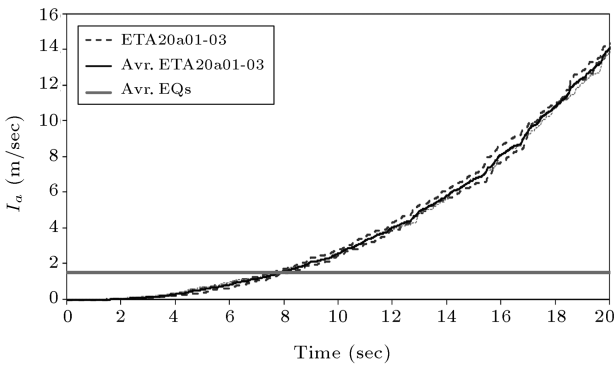


Figure 10. I_a for ETA20a acceleration functions and ground motions.

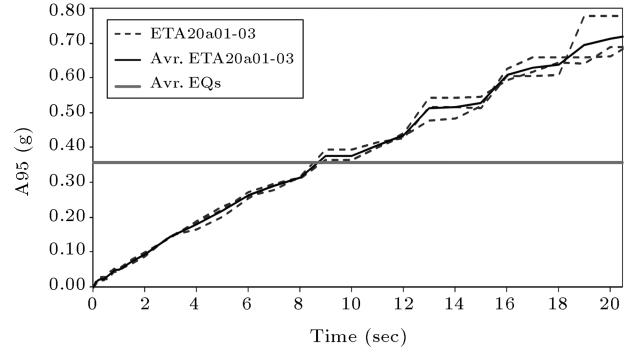


Figure 11. A95 for ET acceleration functions and ground motions.

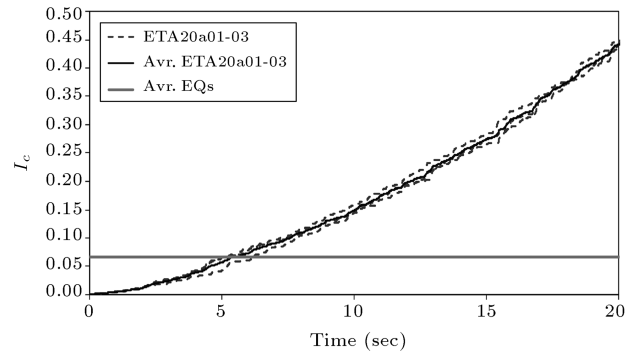


Figure 12. I_c for ET acceleration functions and ground motions.

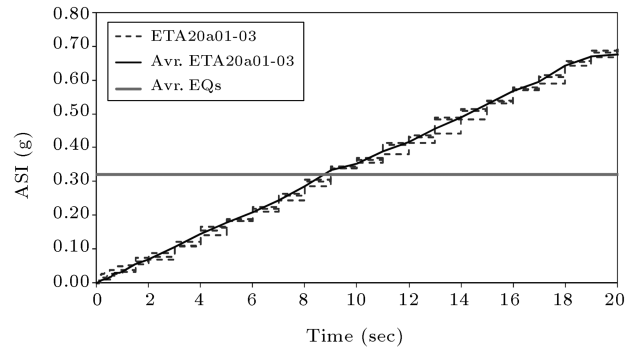


Figure 13. ASI for ET acceleration functions and ground motions.

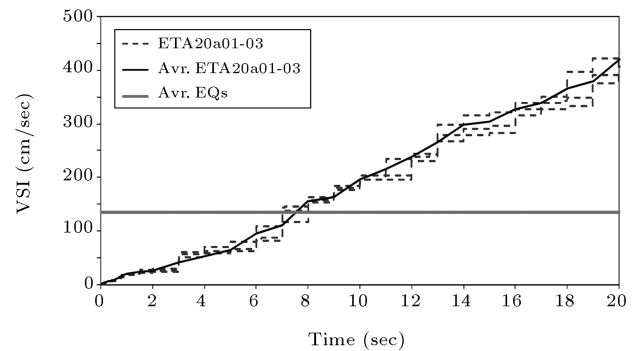


Figure 14. VSI for ET acceleration functions and ground motions.

Period Parameters

The predominant period (T_p) is the period of vibration corresponding to the maximum value of the Fourier amplitude spectrum. It is seen from Figure 15, for ET acceleration functions, this parameter varies between 0.2 seconds and 0.5 seconds, with an average of 0.35 seconds, which is equal to predominant periods of ground motion. This is due to the same soil conditions for earthquakes and ET acceleration functions.

Mean period (T_m) is defined as:

$$T_m = \frac{\sum C_i^2 / f_i}{\sum C_i^2}, \quad (9)$$

where C_i is Fourier amplitude and f_i represent the discrete Fourier transform frequencies between 0.25 Hz and 20 Hz. This is the best simplified frequency content characterization parameter.

Figure 16 shows that the T_m for ET acceleration functions are higher than ground motions.

Peak Velocity-Acceleration Ratio

This parameter reveals the dependence of the magnitude and distance of the earthquake from the site. This

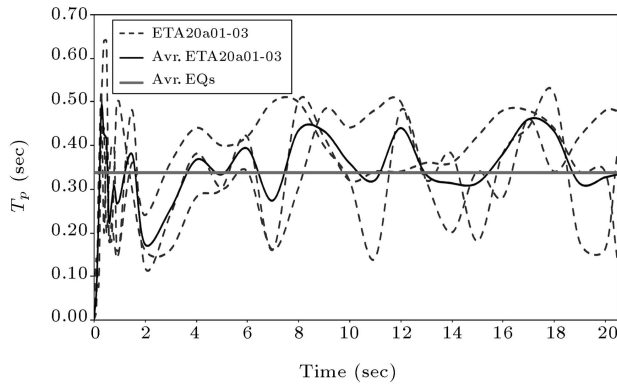


Figure 15. T_p of ET acceleration functions and ground motions.

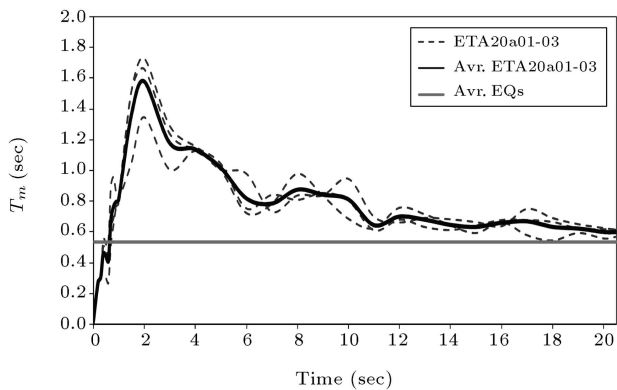


Figure 16. T_m of ET acceleration functions and ground motions.

ratio increases with the increasing magnitude of the earthquake and the increasing source distance to the site. This parameter is depicted in Figure 17.

It is evident that this value is much higher for ET acceleration functions than for ground motions.

Cumulative Absolute Velocity

The Cumulative Absolute Velocity (CAV) is the area under absolute acceleration. This parameter correlates well with the structural damage potential [7].

From Figure 18, the average of earthquakes and ET acceleration functions is the same at $t = 10$ sec. Therefore, some structural damage, which is dependent on CAV, might be the same for selected earthquakes and the ETA20a series of acceleration function results at $t = 10$ sec.

Sustained Maximum Acceleration (SMA) and Velocity (SMV)

SMA is defined as the third highest absolute value of acceleration in the time history. These parameters are depicted in Figures 19 and 20.

It can be seen that these two parameters for

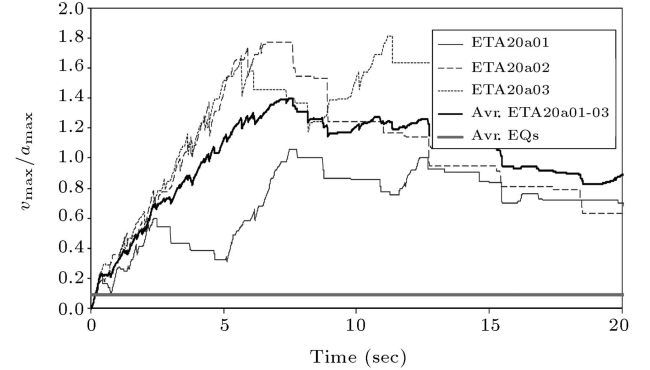


Figure 17. V_{\max}/a_{\max} for ET acceleration functions and ground motions.

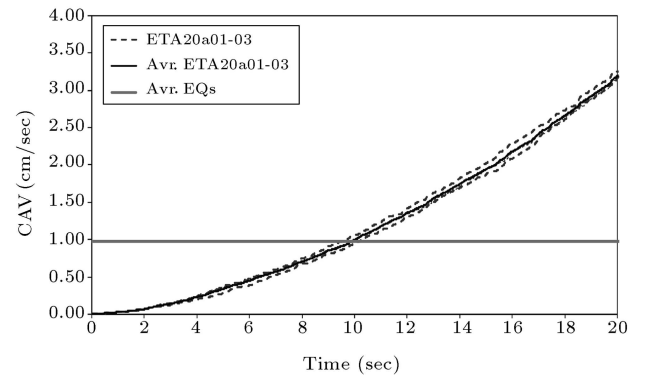


Figure 18. CAV for ET acceleration functions and ground motions.

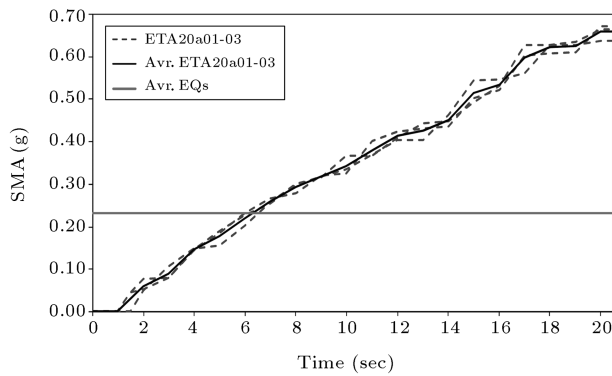


Figure 19. SMA for ET acceleration functions and ground motions.

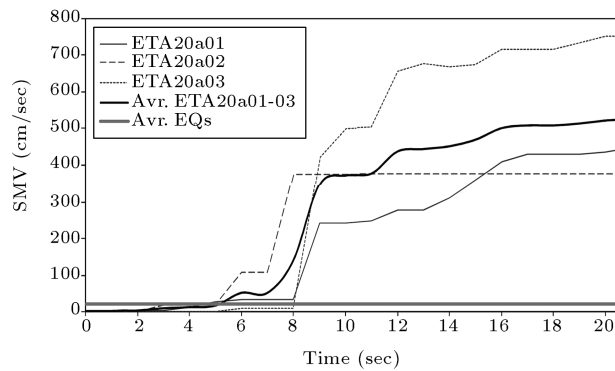


Figure 20. SMV for ET acceleration functions and ground motions.

ground motions are the same at $t = 6$ sec of ET acceleration functions.

Effective Design Acceleration (EDA)

EDA corresponds to the peak acceleration value found after low pass filtering the input time history with a cut-off frequency of 9 Hz [8]. Kennedy proposed that the effective design acceleration be 1.25 times the third highest peak acceleration obtained from a filtered time history.

From Figure 21, the EDA for the average of earthquakes is the same as ET acceleration functions at $t = 8.5$ sec.

CONCLUSIONS

In this study, characteristics of the first set of second generation ET acceleration functions, i.e. ETA20A01~3, as a set of synthesized, intensifying accelerograms have been investigated. These acceleration functions make use of a typical codified design spectrum as a template spectrum. The following conclusions can be drawn, based on the results discussed in this research:

1. Most structurally significant parameters, except en-

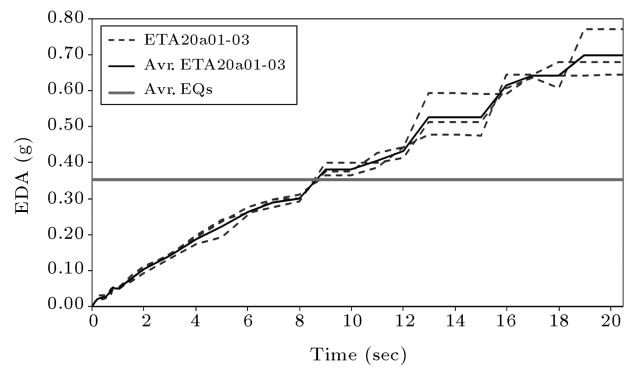


Figure 21. EDA for ET acceleration functions and ground motions.

ergy and amplitude parameters, which correspond to nonlinear behavior, are nearly the same for ET acceleration functions at the time of about $t = 10$ sec (i.e. the target time) and the average of ground motions at short periods.

2. At frequencies between 2.5 and 10 Hz, Fourier amplitudes of ETA20a are the same as the average of selected ground motions. However, at high and very low frequencies, which are not covered in the optimization process, the differences are significant.
3. Intensity parameters for ETA20a acceleration functions around $t = 8$ sec are comparable to the average of selected ground motions.
4. At short periods, energy spectra of ETA20a acceleration functions at $t = 10$ sec are similar to the average of selected earthquakes. However, at middle and long periods, they are not the same, and values from ETA20a acceleration functions are remarkably greater than ground motions.
5. ETA20a acceleration functions are in general not suitable for application in cases involving very short and very high effective periods of vibration. This includes highly nonlinear structures with long periods of vibration (above about 4 sec) on one side, and structures with a very short period of vibration (below about 0.1 sec) on the other side of the spectrum range.

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REFERENCES

1. Elenas, A. "Correlation between seismic acceleration parameters and overall structural damage indices of buildings", *Soil Dyn. and Earthq. Engng.*, **20**(1-4), pp. 93-100 (2000).

2. Estekanchi, H.E., Vafai, A. and Sadeghazar, M. "Endurance time method for seismic analysis and design of structures", *Scientia Iranica*, **11**(4), pp. 361-370 (2004).
3. Joyner, W.B. and Boore, D.M. "Measurement, characterization and prediction of strong ground motion in earthquake engineering and soil dynamic II", *Proc. Am. Soc. Civil Eng. Geotech. Eng. Div. Specialty Conf.*, pp. 43-102, Park City, Utah (June 27-30, 1988).
4. Estekanchi, H.E., Valamanesh, V. and Vafai, A. "Application of endurance time method in linear seismic analysis", *Engineering Structures*, **29**(10), pp. 2551-2562 (2007).
5. Estekanchi, H.E., Arjomandi, K. and Vafai, A. "Estimating structural damage of steel moment frames by endurance time method", *Journal of Constructional Steel Research*, **64**(2), pp. 145-155 (2008).
6. Sarma, S.K. and Yang, K.S. "An evaluation of strong motion records and a new parameter A95", *Earthq. Engng. and Struct. Dyn.*, **15**(1), pp. 119-132 (1987).
7. Kramer, S.L., *Geotechnical Earthquake Engineering*, Prentice Hall Upper Saddle River, Newjersey (1996).
8. Benjamin, J.R. et al. "A criterion for determining exceedance of the operating basis earthquake", *Report EPRI NP-5930, Electric Power Research Inst.*, Palo Alto, California (1988).