SCALING OF EARTHQUAKE ACCELEROGRAMS FOR NON-LINEAR DYNAMIC ANALYSES TO MATCH THE EARTHQUAKE DESIGN SPECTRA

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ABSTRACT :

A complete seismic design of structures requires linear and nonlinear time-history analyses especially for special type buildings. Seismic design codes generally define ground shaking in the form of a response spectrum of acceleration and allow using response spectrum compatible time history records in linear and nonlinear time history analyses. These records can be obtained from natural earthquake records, or can be generated synthetically and artificially. Although using real earthquake records has many advantages, there may exist lack of strong motion earthquake records to satisfy seismological and geological conditions and requirements defined in seismic codes. Artificial accelerograms whose response spectra closely compatible to design response spectra can be generated in either time or frequency domain. Matching techniques are based on scaling of the selected time history in time domain; filtering actual motion in frequency domain by its spectral ratio with the design target spectrum; or elementary wavelets are added or subtracted from the real time history to match a target design spectrum. In this study, the spectrum matching procedures for real accelerograms are summarized and applied to selected real acceleration records to match the proposed Type 1 elastic design spectrum given in the Eurocode 8 for specified seismic region and soil type. Artificial accelerograms, which are compatible with the selected design spectrum, are generated according to specified scenario earthquake. The linear and nonlinear response of single degree of freedom system subjected to the modified and artificially generated time histories acceleration records are compared and the advantages and disadvantages of each one are discussed.

KEYWORDS: Matching techniques, earthquake records, spectrum compatible, artificial records, non-linear analysis

1. INTRODUCTION

Seismic design is traditionally performed for most common structures by the means of equivalent lateral static loading or modal spectrum analyses. Nevertheless, in some cases such as, irregular, highly ductile, critical or higher modes induced structures, conventional response spectral analyses are not capable of estimating maximum responses of linear systems, for which a time-integration scheme is deemed more appropriate (Preumont, 1984). Seismic design codes generally define ground shaking in the form of a response spectrum of acceleration and permit to use spectrally matched natural accelerograms recorded during earthquakes, spectrum compatible artificially generated and synthetic ground motions for the linear or nonlinear analysis of structures in linear and nonlinear time domain analyses.

The attraction of using natural accelerograms is due to the increase of available strong ground motion databases. In the case of using real earthquake records, they have to be organized to match the design spectrum throughout the full spectral range or only over a portion of a specified range that is of interest to the design. Spectral matching may be performed in either the time domain or the frequency domain in such ways: The spectral acceleration values of the selected time history are simply scaled up or down uniformly; an actual motion is filtered in frequency domain by its spectral ratio with the design target spectrum; elementary wavelets are added or subtracted from the real time history to match a target design spectrum (RSPMatch). The spectrum matching procedure begins with an acceleration time history whose characteristics reasonably represent the ground motions expected for the site. Therefore, selection and matching of the input ground motions are critical issues to perform linear and nonlinear response history analyses. The drawback of the use of real time histories lies in trying to match a single ground motion to a design response spectrum that is not intended to represent the motion from an individual earthquake (Naeim and Kelly, 1999). The design response spectrum is generally a result of a statistical analysis that considers the influence of several seismic sources simultaneously, whence the response at different periods may be driven by earthquakes in different sources and the spectrum is effectively the envelope of spectra corresponding to scenarios in each of the sources (Reiter, 1990).

Despite the continued growth of the global strong ground motion databank, suitable records, which have the same earthquake parameters with the site considered such as magnitude, rupture mechanism, source-to-site distance and site classification, can not be obtained in some circumstances (Bommer et al., 2003). This can impose the need to generate spectrum compatible artificial earthquake records using spectral density function and random phases (e.g., SIMQKE) or using non-stationary stochastic vector processes (e.g., TARSCTHS) or synthetically simulated records.

In this study, real earthquake records are selected simply based on magnitude, fault type and ground types prescribed in the Eurocode 8 (2003). The spectrum matching procedures for real accelerograms are summarized and applied to selected real acceleration records to match the proposed Type 1 elastic design spectrum given in the Eurocode 8 for specified seismic region and soil type. Artificial accelerograms, which are compatible with the selected design spectrum, are generated according to specified scenario earthquake. The resulting time histories are investigated in terms of suitability as input to time history analyses of civil engineering structures. The linear and nonlinear responses of single degree of freedom system subjected to these acceleration records are obtained and the advantages and disadvantages of each one are discussed.

2. SELECTION OF REAL EARTHQUAKE RECORDS FOR SPECTRUM MATCHING

In seismic design codes, seismic scenario, which is based on a pair of magnitude, distance and soil conditions, is generally represented by means of a spectral target shape. Guidance given in seismic design codes on how to select appropriate real records is usually focused on compatibility with this response spectrum rather than seismological parameters. Therefore, real earthquake records, which have similar characteristics (magnitude, distance, site condition and faulting type) with the site under consideration, have to be selected to match elastic response spectrum given in the code. When selecting the earthquake records, it is desirable to use earthquake magnitudes within 0.25 magnitude units of the target magnitude (Stewart et al, 2001). Selection of records having appropriate fault-site distances is important especially for near-fault sites. Site conditions have a major effect on the characteristics and frequency content of the strong ground motion records. Even though the ground motions are amplified in soft soils, the high frequency motions are attenuated. Also, in order to preserve non-stationary characteristics of the initial time history, it is essential to start with an acceleration time history whose spectrum is as close to the target spectrum as possible in the period range of interest. A close initial fit also ensures a speedy convergence to the design values.

3. SPECTRAL MATCHING METHODS

There are three methods for modifying actual time histories and two methods to artificially generate time histories to match a given design spectrum:

3.1. Ground Motion Scaling in Time Domain

In this approach, recorded motion is simply scaled up or down by a constant scaling factor uniformly to find out the best match to the target spectrum over a period range of interest, without changing the frequency content. It could be stated that the accelerograms should only be scaled in terms of amplitude. The procedure is based on minimizing the differences between the scaled motion's response spectrum and target spectrum in a least-square sense. The methodology proposed herein considers as "Difference" the squared scaled-to-target difference, evaluated by the integral (Nikolaou, 1998),

$$\left|\text{Difference}\right| = \int_{T_A}^{T_B} \left[\alpha\, S_a^{actual}(T) - S_a^{target}(T)\right]^2 dT \qquad (4.1)$$

where, S_a^{target} and S_a^{actual} are target acceleration response spectrum and acceleration spectrum of the given (actual) time history, respectively. α, T, T_A and T_B are is scaling factor, period of oscillator, lower period of scaling, and upper period of scaling, respectively. In order to minimize the difference, the first derivative of the difference function with respect to the scaling factor has to be zero which lead to definition of scaling factor α, in a discrete form, as

$$\min\left|\text{Difference}\right| \quad \Rightarrow \quad \frac{d\left|\text{Difference}\right|}{d\,\alpha} = 0 \Rightarrow \quad \alpha = \frac{\sum\limits_{T=T_A}^{T_B} \left(S_a^{actual}(T)\ S_a^{target}(T)\right)}{\sum\limits_{T=T_A}^{T_B} \left(S_a^{actual}(T)\right)^2} \qquad (4.2)$$

3.2. Spectral Matching in Frequency Domain

A frequency domain matching methodology uses an actual record to produce a similar motion that matches almost perfectly a target (design) spectrum. In this method, an actual motion is filtered in frequency domain by its spectral ratio with the design target spectrum. Fourier spectral amplitudes of an input motion are modified while the Fourier phases of that remain unchanged during the entire procedure. Preservation of phase characteristics is important for non-linear time domain analyses, because the non-linear solution can be sensitive to the phasing of the individual time history. In order to keep the phases one applies to the signal a real-only "transfer function" (i.e., with a zero-imaginary component), to rescale the Fourier amplitudes. The technique is repeated iteratively until the desired matching is achieved for a certain range of periods. The more iterations results with better compatibility with the target design spectrum (Ozdemir and Fahjan, 2007).

3.3. Spectral Matching in Time Domain

One approach for spectral matching is to adjust the original record iteratively in the time domain to achieve compatibility with a specified target acceleration response spectrum by adding wavelets having specified period ranges and limited durations to the input time history. These wave packets are added at times where there is already significant amplitude in that period range in the time history. This method preserves the overall phasing characteristics and as the time varying (i.e., non-stationary) frequency content of the ground motion (Somerville, 1998). The resulting records each have an elastic response spectrum that is coincident (within a tolerance) with the target spectrum. This procedure was first proposed by Kaul (1978) and was extended to simultaneously match spectra at multiple damping values by Lilhanand and Tseng (1987). Although this procedure is more complicated than the frequency domain matching procedure, in most cases it can preserves the non-stationary character of the reference time history. Abrahamson (1992) developed RSPMATCH software modifying the Lilhanand and Tseng algorithm that preserves non-stationary character of the reference ground motion for a wider range of time histories.

3.4. Spectrum Compatible Artificial Record Generation

The principal goal of artificial accelerograms generation method is to obtain a design acceleration time history that will have a response spectrum as close as desired to the predetermined target spectrum. Such accelerograms can be obtained in frequency domain using different assumptions with iterative procedures. The computer program SIMQKE (Gasparini and Vanmarcke, 1976) computes a power spectral density function from a specified smooth response spectrum and uses this function to derive the amplitudes of sinusoidal signals which have random phase angles uniformly distributed between 0 and 2π. The sinusoidal motions are summed to generate a time history record. An iterative procedure can be invoked to improve the match with the target response spectrum, by calculating the ratio between the target and actual response ordinates at selected frequencies. In order to get other characteristics of artificial spectrum-compatible record, such as duration, it is necessary to obtain supplementary information about the expected earthquake motion apart from the response spectrum. The code TARSCTHS (Papageorgiou et al., 2002) uses non-stationary stochastic vector processes to generate artificial time histories from a user defined elastic response spectrum. The iterative scheme is applied in frequency domain where the phase angles of the desired motion are randomly generated.

4. CRETERIA FOR EVALUATION OF MATCHED ACCELEROGRAMS

Even though, it is possible to obtain acceleration time histories that are almost completely compatible with the elastic design spectrum by spectral matching or artificial acceleration generation, the resulting accelerograms must have realistic characteristics of earthquakes in terms of amplitude, frequency content and duration. In many cases, generated accelerograms have an excessive number of cycles of strong motion, and consequently have unrealistically high energy content. Also, non-stationary characters of the initial time history such as, availability P and S waves arrivals particularly at longer periods, can be altered if the shape of the Fourier spectrum is changed significantly (Abrahamson, 1992). A baseline correction and filtering should be performed to the generated acceleration time histories, and the corrected time-history should be checked again for spectrum compatibility. The acceleration, velocity and displacement time histories should be examined to ensure that they are reasonably close to the target values in terms of peak values, wave form, strong shaking duration and other critical features such as the near-fault velocity pulse. Power spectral density function should be examined to ensure a board distribution of energy in the final spectrum-compatible motion as a function of Fourier period and there are no significant deficiencies in the energy at periods important to the structure.

5. EUROCODE 8 DESIGN SPECTRA and SELECTION CRITERIA for RECORDS

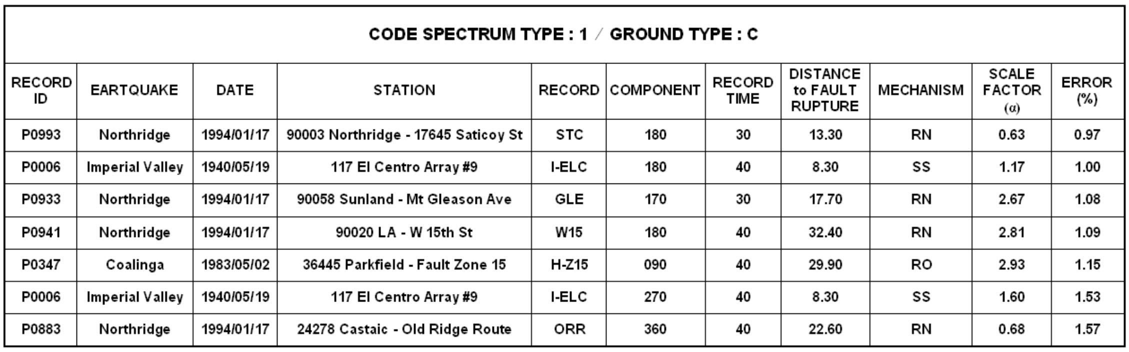
In Eurocode 8, the shape of horizontal elastic response spectrum is defined by four branches using the values of the periods T_B, T_C and T_D which take varying values for the five local site classes A, B, C, D, and E and two ranges of earthquake magnitudes. It is recommended that the Type 2 spectrum is adopted for surface magnitude, M_s, not greater than 5,5. Otherwise, Type 1 elastic response spectrum is used. Eurocode 8 permits using of recorded, artificial and simulated accelerograms for earthquake time history analysis. A minimum of 3 accelerograms should be used where the mean of the zero period spectral response acceleration values should not be smaller than the value of "a_g S" for the site in question. The mean values of 5% damping elastic spectrum, calculated from all time histories, should not be less than 90% of the corresponding values of the code elastic response spectrum at periods range between $0{,}2T_1$ and $2T_1$, where T_1 is the fundamental period of the structure. For artificially generated acclereograms, when site-specific data are not available, the minimum duration T_s of the stationary part of the accelerograms should not be less than 10 sec and the duration of the accelerograms shall be consistent with the magnitude and the other relevant features of the seismic event underlying the establishment of a_g .

In this study, seven different design earthquakes have been generated by time scaling and SIMQKE, TARSCTHS and RSPMatch programs to match Type 1 response spectrum. Considering both importance factor and structural behavior factor to be unity, Type 1 design response spectra for ground type C and regional factor, a_g, to be 0.3g is selected as target response spectrum. The proposed design spectrum may represent the ground motion of a point at epicentral distance of 15-30 km from an earthquake with moment magnitude of 6.6-7.5. The candidate real accelerograms used for scaling and RSPMatch analyses are obtained from Pacific Earthquake Engineering Research (PEER) Center, NGA strong motion database (PEER, 2005).

6. DISCUSSIONS and CONCLUSIONS

The above mentioned four methods namely, Time scaling, SIMQKE, TARSCTHS and RSPmatch are used to generate seven (7) acceleration time histories to fit the proposed design spectrum. Acceleration, velocity and displacement spectra of the output time histories are compared with the correspondent target design spectra. The nonlinear response of SDOF for the generated time histories are examined by computing the ductility factor (μ) for different structural behavior factors, R=1,2,4,8. In real earthquake records, average of the ductility factor is expected to be equal to structural behavior factor at longer periods (equal displacement rule) especially for velocity and displacement sensitive spectral regions (Chopra, 2000). Equal displacement rule may not be satisfied by time histories recorded near the source. In the Time scaling method the best fitted records with the specified design spectrum are selected among the existing real time histories in Peer database and listed in Table 1. The average of selected records acceleration, velocity and displacement spectra have some differences up to %25 from the design spectra for some period ranges as it is noticed in Figure 1. The average nonlinear response of the scaled time histories has compatible behavior with the equal displacement rule.

Table 1 List of earthquake records used for time scaling method



CODE SPECTRUM TYPE : 1 / GROUND TYPE : C

RECORD ID	EARTQUAKE	DATE	STATION	RECORD	COMPONENT	RECORD TIME	DISTANCE to FAULT RUPTURE	MECHANISM	SCALE FACTOR (α)	ERROR (%)
P0993	Northridge	1994/01/17	90003 Northridge - 17645 Saticoy St	STC	180	30	13.30	RN	0.63	0.97
P0006	Imperial Valley	1940/05/19	117 El Centro Array #9	I-ELC	180	40	8.30	SS	1.17	1.00
P0933	Northridge	1994/01/17	90058 Sunland - Mt Gleason Ave	GLE	170	30	17.70	RN	2.67	1.08
P0941	Northridge	1994/01/17	90020 LA - W 15th St	W15	180	40	32.40	RN	2.81	1.09
P0347	Coalinga	1983/05/02	36445 Parkfield - Fault Zone 15	H-Z15	090	40	29.90	RO	2.93	1.15
P0006	Imperial Valley	1940/05/19	117 El Centro Array #9	I-ELC	270	40	8.30	SS	1.60	1.53
P0883	Northridge	1994/01/17	24278 Castaic - Old Ridge Route	ORR	360	40	22.60	RN	0.68	1.57

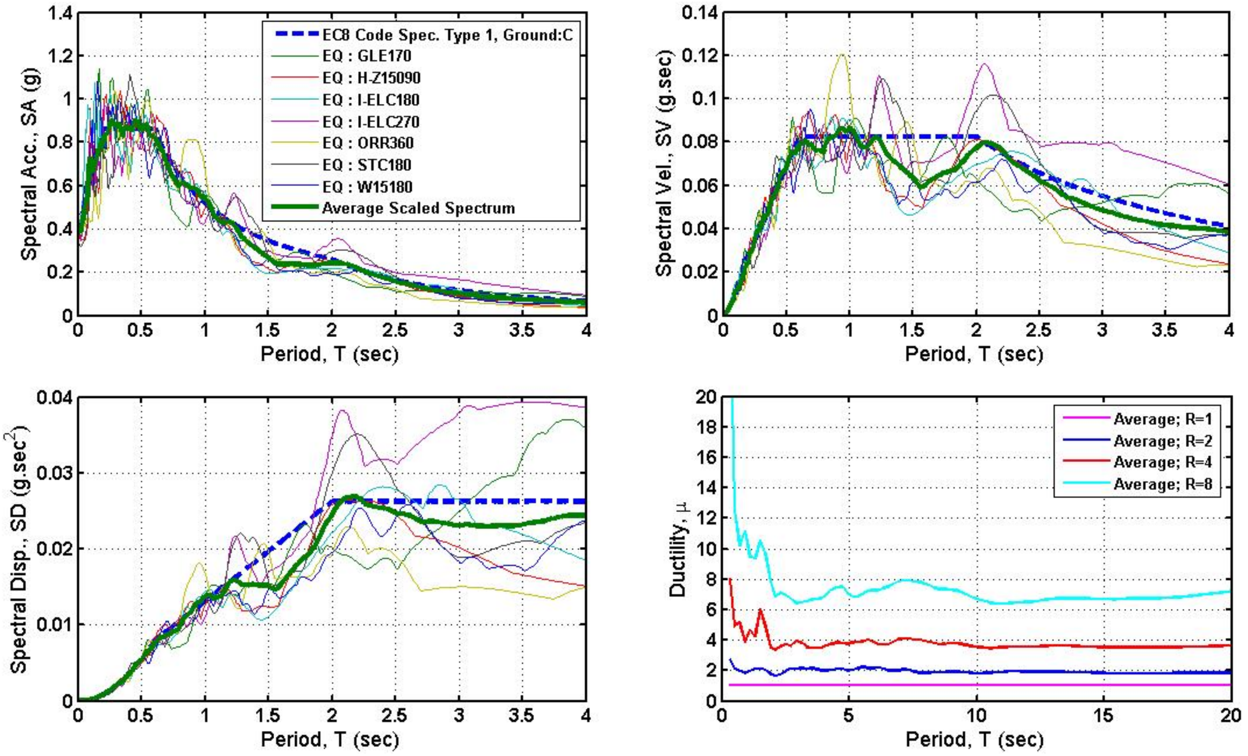


Figure 1 Acceleration, velocity and displacement spectra and ductility demand for time scaled records

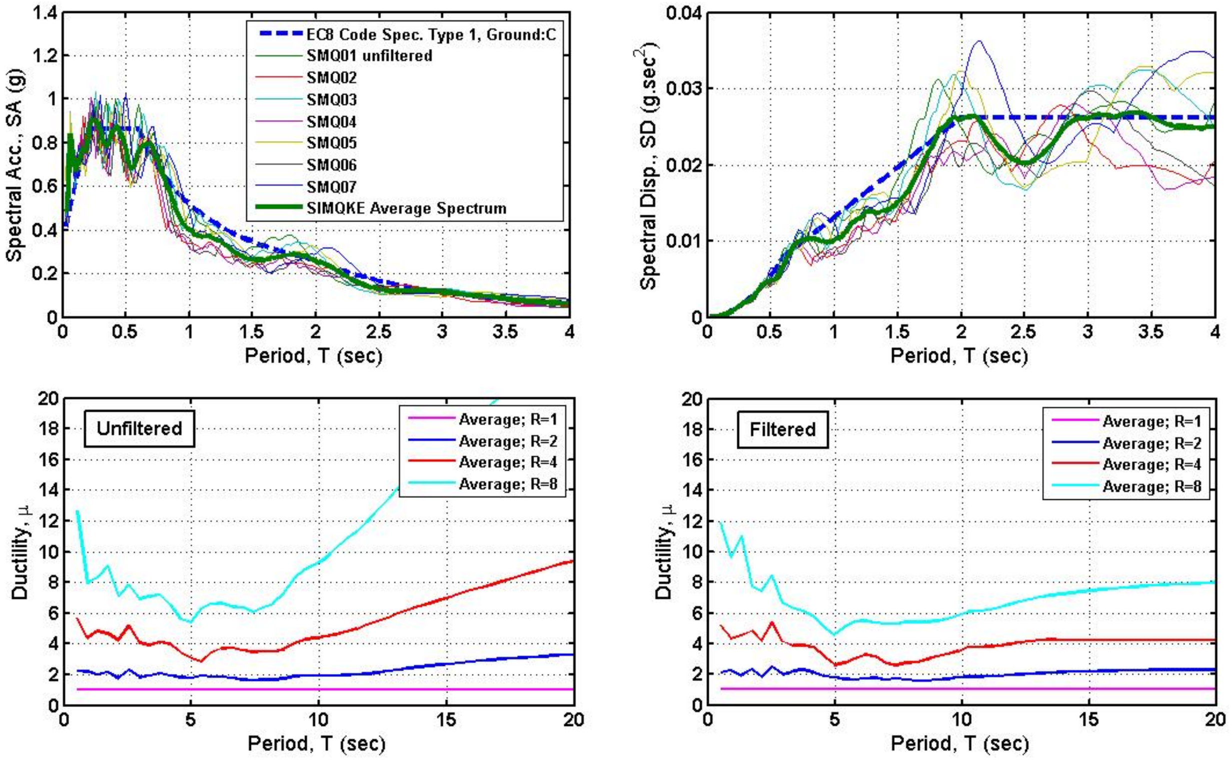


Figure 2 Acceleration, velocity and displacement spectra and ductility demand for SIMQKE generated records

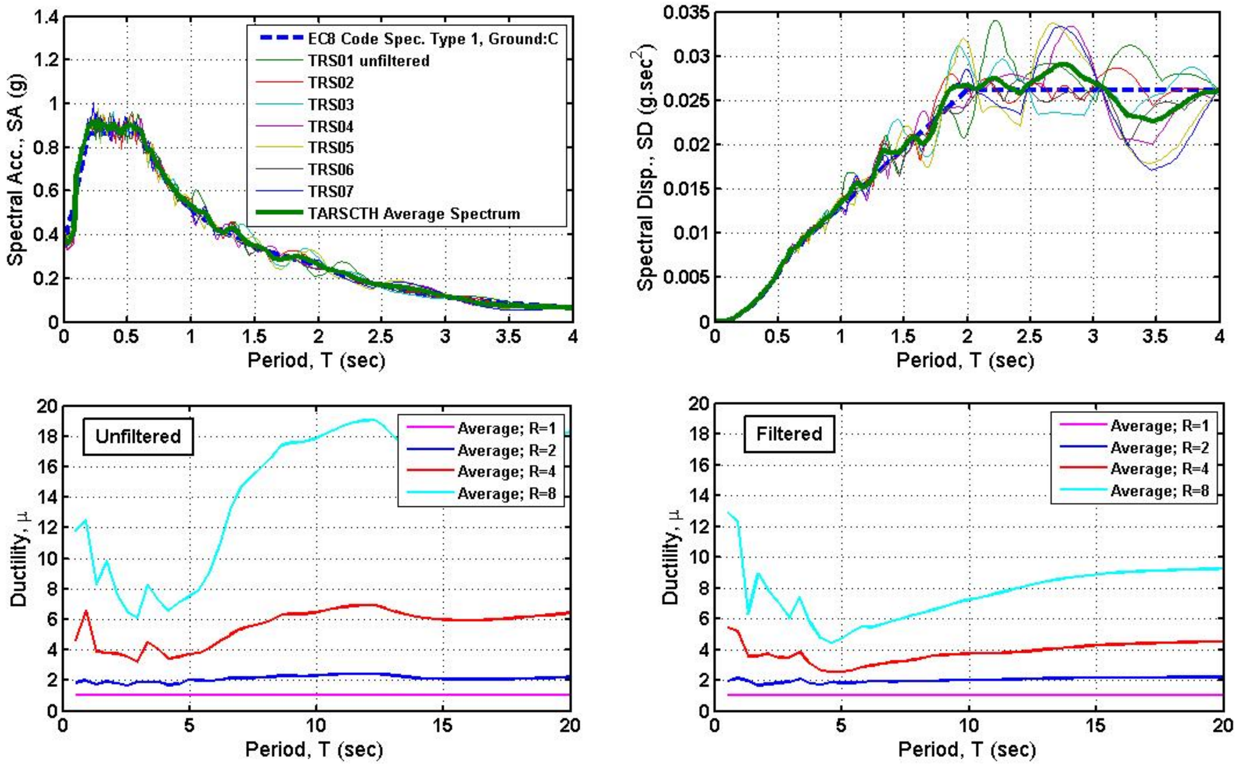


Figure 3 Acceleration, velocity and displacement spectra and ductility demand for TARSCTH generated records

Table 2 List of candidate earthquake records used for RSPMatch

CODE SPECTRUM TYPE : 1 / GROUND TYPE : C									
RECORD ID	EARTQUAKE	DATE	STATION	RECORD	COMPONENT	RECORD TIME	DISTANCE to FAULT RUPTURE	MECHANISM	SCALE FACTOR (α)
P0905	Northridge	1/17/1994	24389 LA - Century City CC North	CCN	360	25.7	25.7	RN	1.59
P0906	Northridge	1/17/1994	90015 LA - Chalon Rd	CHL	70	23.7	23.7	RN	1.73
P0910	Northridge	1/17/1994	90016 LA - N Faring Rd	FAR	90	23.9	23.9	RN	1.49
P0166	Imperial Valley	10/15/1979	6621 Chihuahua	H-CHI	12	28.7	28.7	SS	1.41
P0884	Northridge	1/17/1994	24303 LA - Hollywood Stor FF	HOL	90	25.5	25.5	RN	1.48
P0810	Cape Mendocino	4/25/1992	89324 Rio Dell Overpass - FF	RIO	270	18.5	18.5	RN	1.00
P1022	Northridge	1/17/1994	78 Stone Canyon	SCR	90	22.2	22.2	RN	1.17

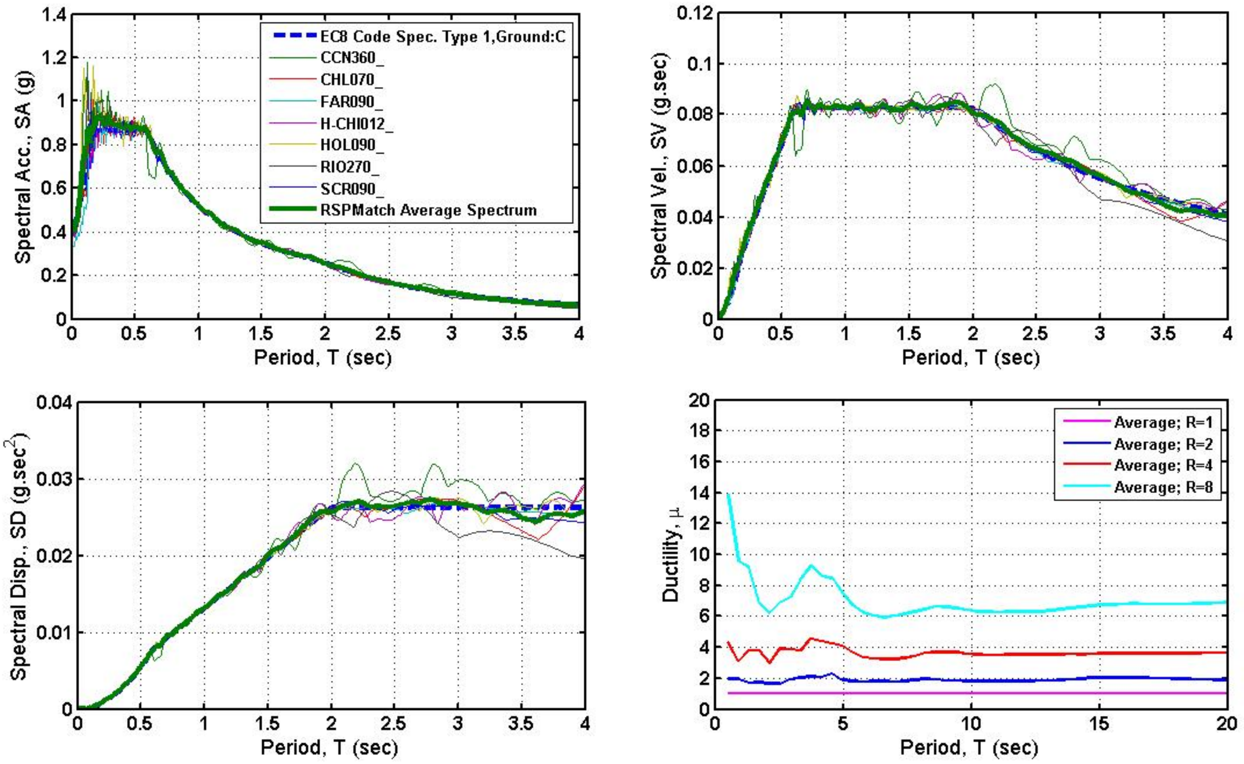


Figure 4 Acceleration, velocity and displacement spectra and ductility demand for RSPMatch generated records

SIMQKE program is used to generate artificial acceleration time histories fitted with the proposed design spectrum with the option to have trapezoidal intensity envelope with earthquake rise time, earthquake level time, desired duration of acceleration and desired maximum ground acceleration as 2.5 sec, 12 sec, 35 sec and 0.3 g, respectively. The output time histories are filtered (0.1-20Hz) and corrected for the baseline. The average of selected records acceleration, velocity and displacement spectra have inadequate fitting for longer periods with differences up to %26 from the design spectra for some period ranges as it is noticed in Figure 2. The average nonlinear response of the scaled time histories has incompatible behavior with the equal displacement rule in velocity sensitive region. For option with no envelope, non realistic records that do not represent the general characteristics of real earthquakes are generated. Even though the unfiltered time histories have the same fit for the design spectrum as filtered time histories, unrealistic nonlinear behavior can be observed in Figure 2 for the valid period range (0.1s-10s). TARSCTHS program requires moment magnitude and epicentral distance of scenario earthquake to compute duration. The same observation can be noticed for the acceleration time histories artificially generated by TARSCTHS as shown in Figure 3. A better fitting to design spectrum but worse estimation in the nonlinear response compared to SIMQKE can be noted.

RSPMatch program requires a set of earthquake records that initially have considerable compatibility with the target spectrum. The list for initially selected records is given in Table 2. The matching procedure is not robust and program requests a lot of parameters related to additional wavelet iterations. The convergence is not guaranteed for many candidate records. The average of selected records acceleration, velocity and displacement spectra have excellent fit with the design spectra for some period ranges as it is noticed in Figure 4. The average nonlinear response of the scaled time histories has compatible behavior with the equal displacement rule.

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