VALIDATION OF ENERGY-COMPATIBLE AND SPECTRUM-COMPATIBLE (ECSC) SYNTHETIC MOTIONS USING NONLINEAR STRUCTURAL ANALYSES

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ABSTRACT

In current design practice, ground motion effects on structures are represented by an elastic response spectrum, yet the response spectrum doesn't contain other important ground-motion features such as energy build-up, duration as well as ground-motion nonstationarity, which are found to be important in seismic analysis of certain types of structures. In this study, a stochastic ground-motion simulation and modification technique is developed to generate energy-compatible and spectrum-compatible (ECSC) synthetic motions through wavelet-packet characterization and modification. The ECSC method significantly advances traditional ground-motion modification approaches, because it generates ground motions that not only match target spectral accelerations, but also match other important parameters such the Arias intensity and its temporal accumulation, as well as measures of ground-motion duration. A salient feature of the ECSC method is that ground motions are modified in both frequency and time domain iteratively. Examples are presented to demonstrate the great similarity between the ECSC simulated motion and its recorded counterpart. Further, nonlinear structural responses subjected to ECSC ground motions and their recorded counterparts are compared using a variety of structural models, including 4-, 8-, 12-, and 20-story reinforced concrete perimeter frame models. The numerical analyses demonstrated that structural responses by the ECSC ground motions are very consistent with that by the recorded motions. Therefore, the ECSC method can find important applications in time history analyses of nonlinear systems in performance-based earthquake design.

Keywords: Synthetic ground motion, spectrum matching, ground-motion duration, wavelet packet

1. INTRODUCTION

Performance-based earthquake engineering often requires ground-motion time-history analyses to be performed, but very often, actual recorded ground motions are limited. Recorded motions at design level are particularly rare, and may not be sufficient for characterizing statistical distribution of structural responses. In current engineering practice, ground-motion time histories need to be selected and modified from recorded strong-motion database (Wang 2010, 2011; Wang et al. 2015; Youngs et al. 2007), or generated through either deterministic or stochastic numerical approaches.

Given a response spectrum, ground motions that reasonably match the target response spectrum are not unique, because the response spectrum provides only a partial picture of real ground-motion characteristics and doesn't contain other important features such as energy build-up, duration as well as ground-motion nonstationarity. These parameters have been found to be important in the analysis of certain types of structures. For example, Chandramohan et al. (2016) concluded that ground-motion duration is important in risk assessments of structural collapse; Wang (2012) demonstrated that the Arias intensity (Ia), in addition to spectral acceleration, is important for predicting seismic slope displacements.

Therefore, rigorous ground-motion selection and modification process requires consideration of multiple intensity measures (IMs) collectively. For this purpose, a stochastic ground-motion simulation and modification technique is proposed by Huang and Wang (2016) to generate energy-compatible and spectrum-compatible (ECSC) synthetic motions through wavelet-packet characterization and modification. Using the method, one can simulate ground motions with target time- and frequency-domain characteristics, including response spectra, cumulative Arias intensity and duration. In this study, the performance of the ECSC ground motions is systematically validated using a variety of structural models, including 4-story, 8-story, 12-story, and 20-story reinforced concrete perimeter frame model. By using actual recorded ground motions and ECSC simulated motions, these extensive numerical simulations demonstrate that the ECSC ground motions are reliable and unbiased in nonlinear seismic analyses of these structures.

2. STOCHASTIC SIMULATION OF ENERGY COMPATIBLE AND SPECTRUM COMPATIBLE GROUND MOTIONS

2.1. Stochastic modeling of ground motions using wavelet packets

Synthetic ground motions can be generated through numerical methods. As one special form of spectral presentation, the wavelet packet transform was recently used to simulate nonstationary ground motions by Yamamoto and Baker (2013). The wavelet packet transform is an advanced time-frequency analysis tool that decomposes a ground-motion time series $x(t)$ into a set of wavelet packets localized in the time (t) and frequency (f) domain. The stochastic method has also been extended for simulating spatially correlated ground motions by Huang and Wang (2015a, 2015b). For a time series $x(t)$, the wavelet packet coefficient is defined as:

$$c_{j,k}^{i} = \int_{0}^{\infty} x(t)\psi_{j,k}^{i}(t)dt \tag{1}$$

where $\psi_{j,k}^{i}(t)$ denotes the wavelet packet basis function, which is selected as the Meyer wavelet function. Figure 1 illustrated an example of decomposition of a ground-motion time history using wavelet-packet analysis. Given an acceleration time history Figure 1(a), the time and frequency distribution of squared wavelet-packet coefficients is the wavelet-packet spectrum (WPS), as presented in Figure 1(b). In this example, the wavelet-packet spectrum contains 16 columns in the time domain (2.56 sec to 40.96 sec) and 256 rows in the frequency domain (ranging from 0.1953 Hz to 50 Hz). Ground-motion time history $x(t)$ can be precisely reconstructed through inverse transformation, i.e., summation of wavelet packets over all columns and rows in the wavelet-packet spectrum.

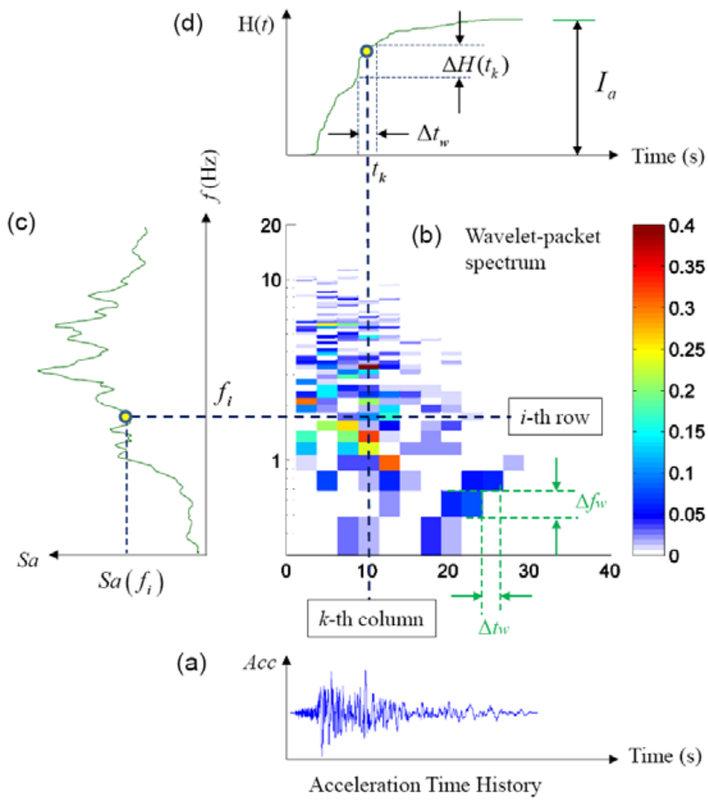


Figure 1: Wavelet-packet spectrum, showing the distribution of squared wavelet-packet coefficients of a recorded ground-motion time history.

2.2. Algorithm for ECSC ground-motion simulation and modification

Figure 1(d) illustrates the temporal accumulation of Arias intensity. The accumulation function $H(t)$ contains information about the total energy and duration of the ground motion, which can be altered by applying a time-varying modulating function to the acceleration amplitude. On the other hand, the spectral acceleration, $Sa(f)$, can be modified by adjusting the wavelet-packet coefficients in the corresponding frequency, as shown in Figure 1(c). Due to orthogonal property of the wavelet packet decomposition, time/frequency characteristics of ground motion can be modified rather independently. The algorithm for ECSC ground-motion simulation and modification is briefly described as follows:

1. Generate a seed motion given a specific earthquake scenario: Given an earthquake scenario (M, R, V_{s30} etc.), an seed motion $x(t)$ can be first generated based on predictions equations of wavelet-packet parameters (Yamamoto and Baker 2013).

2. Adjust the wavelet-packet coefficients in frequency- and time-domain: The seed motion is then modified in frequency- and time-domain iteratively via applying a multiplier to the wavelet packet coefficients at different frequencies, and applying a time-varying enveloping function over the time history. (a) In the frequency domain, the time instance t_k corresponding to the occurrence of peak acceleration of the 5% damped 1-DOF linear oscillator is first determined. Wavelet packets coefficient corresponding to the time t_k and frequency f_i is then modified by multiplying a weight factor, $w(i,k)$, which is determined according to the ratio of the target spectral acceleration to the simulated spectral acceleration at frequency f_i. (b) In the time domain, accumulation of Arias intensity, $H(t)$, corresponds to the summation of squared acceleration over time. To match the energy build-up process and duration, an piece-wise modulating function A(t) can be estimated to multiple the series $x(t)$ in each time interval, such that $H(t)$ function of the modified time history A(t)$x(t)$ matches the given target $H(t)$.
3. Evaluate compatibility of $H(t)$ and $Sa(f)$: The mean squared errors (MSE) is adopted to quantify the relative difference in $Sa(f)$ and $H(t)$ resulted from the simulated and the target motion. Step 2 are iterated until the *MSE* in *Sa* and $H(t)$ reach a desired level. Finally, baseline correction on the modified accelerogram will be performed to avoid drift in velocity and displacement time history.

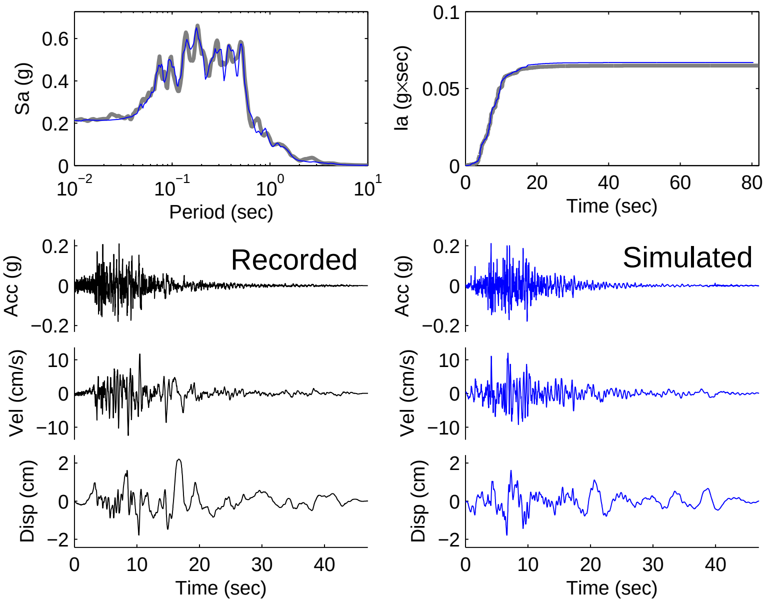


Figure 2: Comparison of time histories, response spectra and Arias intensity build-up between the recorded and the simulated ground motions

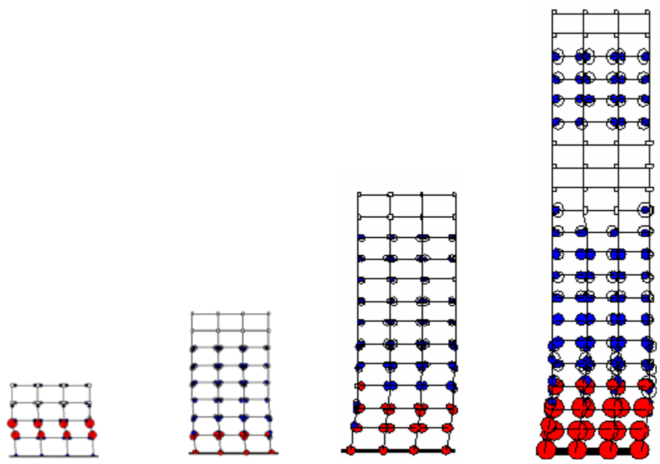
The similarity of real recorded motion (target) and ECSC simulated motion is illustrated in Figure 2, where a recorded ground-motion recording (in black line) from the NGA strong-motion database recorded at the Griffith Park station during the 1994 Northridge earthquake and its ECSC simulated counterpart (in blue line) are compared side by side. By visual inspection, the simulated motion agrees excellently with the recorded one in terms of response spectra and Arias intensity build-up (including durations).

In this study, 50 recorded ground motions from the NGA strong-motion database are selected in the validation test. They are from three large earthquakes in California, including the 1979 Imperial Valley earthquake, the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake. Following the ECSC procedure, 50 ECSC synthetic motions are "reproduced" to form an ECSC dataset. Comparisons of the ECSC and the NGA datasets can be found in Huang (2016).

3. TIME HISTORY ANALYSES OF BUILDING RESPONSES USING ECSC AND NGA GROUND MOTIONS

3.1. The building model

In this section, the ECSC synthetic motions are validated against record motions in analyzing nonlinear building responses. The structure models adopted in this study are four-story, eight-story, twelve-story and twenty-story modern reinforced concrete perimeter frame buildings designed according to the 2003 International Building Code and ASCE7-02. The finite element building models were developed in OpenSees by Haselton (2007), as shown in Figure 3. The building models represent typical ductile frame systems with first-mode periods of 1.12 s, 1.71 s, 2.01 s and 2.63 s. The models have been used by the PEER GMSM Working Group to conduct benchmark tests on various ground motion selection and modification methods (Haselton 2009). .

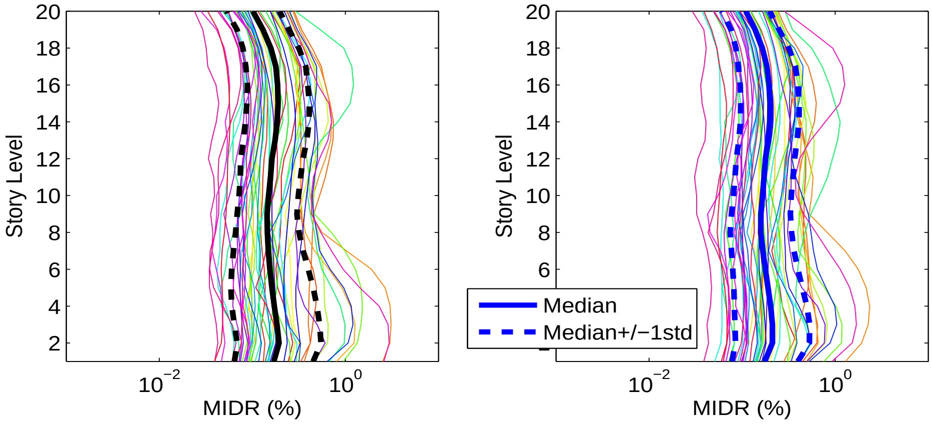


(a) 4-story (b) 8-story (c) 12-story (d) 20-story

Figure 3: Structural model used in time history analyses; Deformed mesh and plastic hinges developed during shaking (Haselton 2007)

3.2. Predicted structural response

Nonlinear numerical structural analyses are performed to investigate the seismic response of the four reinforced concrete perimeter frame buildings using ground motions from the NGA and ECSC datasets. The maximum inter-story drift ratio of all stories (MIDR) is used to evaluate the seismic response. Figures 4(a) and 4(b) show the distribution of the MIDRs of the 20-story building for each story using the two datasets, with their mean and standard deviation highlighted in both figures. The story-by-story distribution of MIDRs provides important details for structural optimization. For each story, MIDRs approximately follow a lognormal distribution. Figure 5 summarizes predicted median MIDR and median ± one standard deviation curves of four buildings using ground motions from the NGA and ECSC datasets. It can be observed that the MIDR distribution of the ECSC dataset is very consistent with that of the NGA dataset. Consistent results can be observed for all four building models, indicating the capacity of the ECSC method in capturing nonlinear structural responses.



(a) NGA records (b) ECSC motion

Figure 4: Distribution of the story-by-story MIDRs of the 20-story building using (a) NGA and (b) ECSC datasets.

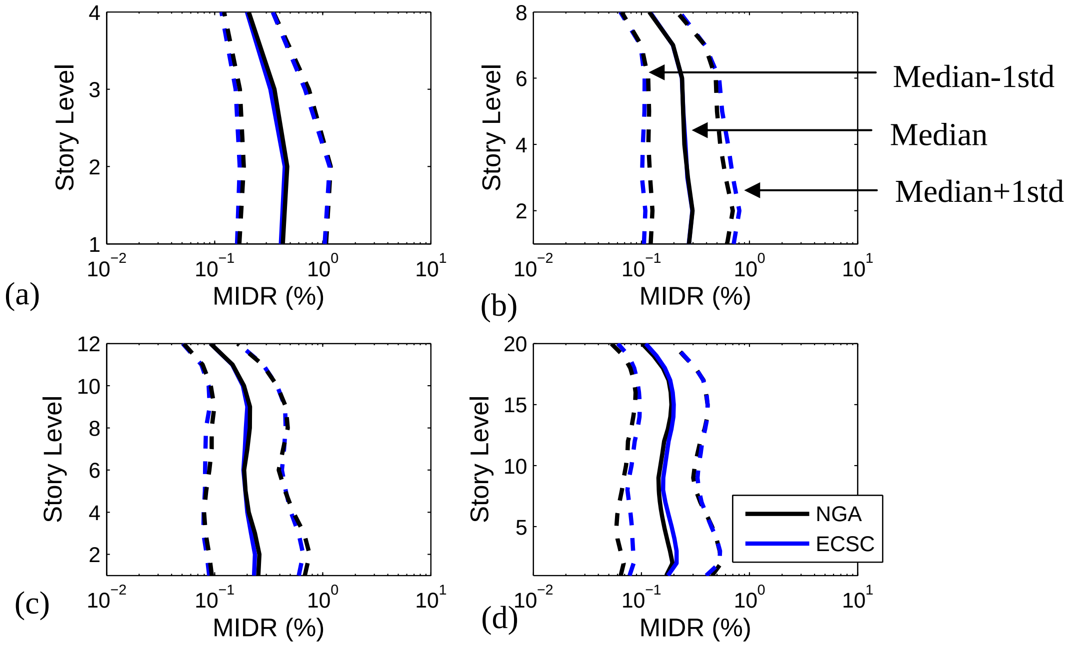


Figure 5: Comparison of median and median ± 1std MIDRs in (a) 4-story building, (b) 8-story building, (c) 12-story building and (d) 20-story building

Further, one-to-one comparison of the MIDRs from the recorded motion and its simulated counterpart is conducted. For each pair of motions, the residual MIDR is defined as:

$$r_{\ln MIDR} = \ln(MIDR_{NGA}) - \ln(MIDR_{ECSC}) \tag{2}$$

where $MIDR_{NGA}$ and $MIDR_{ECSC}$ denote the maximum inter-story drift ratio calculated using the NGA ground motion and its ECSC counterpart, respectively. Figure 6 shows the statistical distribution of MIDR residuals for the four types of buildings. It is seen that the median of residuals is well bounded within ±0.1, i.e., the difference is less than 10%. Note that the one-to-one comparison is a more stringent test than comparison of the overall distribution in Figure 5.

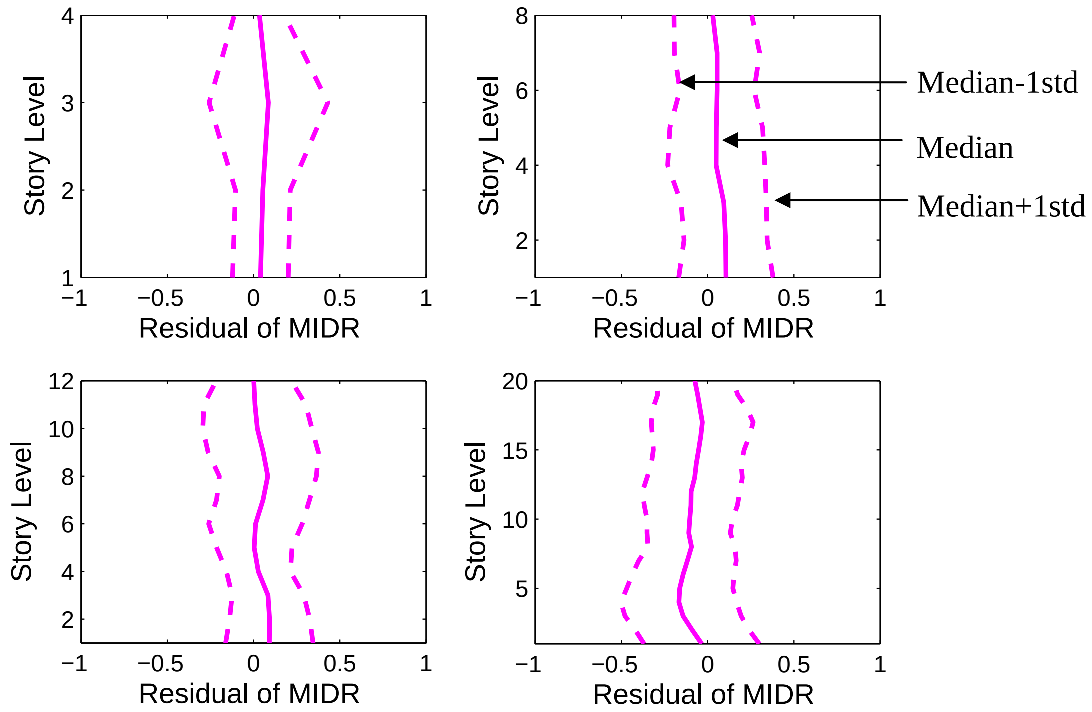


Figure 6: Median and median±1std of residual MIDRs in (a) 4-story building, (b) 8-story building, (c) 12-story building and (d) 20-story building

4. CONCLUSIONS

In this study, a new ground-motion simulation and modification procedure is presented that allows the generation of energy-compatible and spectrum-compatible (ECSC) ground motions through wavelet-packet characterization and modification. The wavelet-packet transform has basis functions that are orthogonal and localized in time and frequency domains. The salient feature allows for ground-motion time histories to be flexibly adjusted in frequency domain and time domain simultaneously, thus, modifying their response spectrum and cumulative energy. The procedure is based on three key steps, starting from prediction of a seed motion using seismological constraints (M, R, V_{s30}), followed by iterative adjustments of the wavelet-packet spectrum in both time- and frequency-domain; finally, evaluating compatibility of response spectrum and cumulative energy of the simulated motion with targets.

The simulated ECSC ground motions have similar spectral accelerations, cumulative Arias intensity and durations compared with their counterparts recorded in the PEER-NGA database. To validate the ECSC ground motions, nonlinear structural responses subjected to the ECSC ground motions and their recorded counterparts are compared using four reinforced concrete perimeter frame models. The numerical analyses demonstrated that the NGA recorded and the ECSC simulated ground motions result in very consistent nonlinear structural responses, and the ECSC motions can be well used to estimate the nonlinear performance of structures under earthquakes. More examples to validate the ECSC ground motions using other structural types or geotechnical systems can be found in Huang (2016).

5. ACKNOWLEDGMENTS

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