Evaluation of Synthetic Ground Motions on Seismic Performance of Sliding Blocks and Tall Buildings

Duruo Huang[a]* and Gang Wang[b]

[a] *Department of Civil and Environmental Engineering and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong*
[b]*Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong*
* huangdr@ust.hk (*corresponding author's E-mail)*

Abstract

In current design practice, ground motion effects on geotechnical systems and earth structures are represented by an elastic response spectrum, yet the response spectrum doesn't contain other features such as ground-motion duration, Arias intensity and its build-up as well as nonstationarity, which are found to be important in seismic assessment of civil infrastructures. Recently, a stochastic method is developed to generate energy-compatible and spectrum compatible (ECSC) synthetic ground motions that not only match target response spectrum, but also match other important parameters such as Arias intensity and its build-up, as well as duration. In this study, the performance of synthetic motions generated using ECSC and SIMQKE methods is validated using Newmark sliding block analyses, which predicts seismically induced slope displacement, and is compared with those computed using recorded ground motions in the NGA database. Time history analyses of a steel structure have also been conducted subjected to synthetic and actual recorded motion sets. Numerical analyses demonstrate that ECSC synthetic ground motions can provide unbiased estimation of seismic slope displacements and tall building responses.

Keywords: Synthetic ground motions, Wavelet packets, Newmark sliding block analyses

1. Introduction

In performance-based earthquake engineering, ground motions are needed to conduct time history analyses for civil structures and earth systems. Real recorded ground motions at design level are rare, and in some conditions inadequate to characterize response distribution of complex infrastructures and geotechnical systems. In recent years, ground motion simulation technology has been actively studied and developed [1-4]. One remarkable example is SIMQKE, which generates synthetic ground motions that match the target response spectrum through iterative modification of Fourier component of modulated Gaussian random process [5]. However, it is worth mentioning that SIMQKE can only generate stationary time histories whose frequency content is unchanged with time. Given a target response spectrum, ground motions that match the spectrum can be many, since the response spectrum provides only a partial picture of ground-motion characteristics. Some other important features, such as Arias intensity, ground-motion duration, which are found important in seismic analyses of certain type of structures or geotechnical systems are not reflected by a response spectrum. For instance, Wang [6] reported that the Arias intensity is significant for estimation of seismic slope displacement; Du and Wang [7] demonstrated that using vector intensity measures can efficiently predict seismic slope displacements.

Therefore, contemporary ground-motion simulation and modification technique requires consideration of multiple intensity measures collectively instead of barely accounting for a target response spectrum. Recently, Huang and Wang [8] proposed a ground-motion simulation and modification method that generates energy-compatible and spectrum-compatible (ECSC) synthetic ground motions based on wavelet-packet characterization. The stochastic method was initially proposed by Yamamoto and Baker [9] and was extended by Huang and Wang [10-12] to simulate spatially correlated ground motions. The method makes full use of wavelet packet transform that has orthogonal basis functions and localized in time and frequency domains, which facilitates flexible adjustment of ground-motion time histories in both time and frequency domains.

In this study, the performance of synthetic ground motions generated using two methods, namely the ECSC and SIMQKE, is validated using Newmark sliding blocks and a steel structure model. By comparing system responses between synthetic motions and actual recorded motions, it is reported that the ECSC ground motions provides unbiased estimation of seismic slope displacements and tall building responses.

2. Methodology

2.1 ECSC synthetic ground motions

The ECSC ground-motion simulation and modification technique proposed by authors is adopted in this study to generate synthetic ground motions. The wavelet packet based method has several noticeable features: (*i*) It can practically characterize both amplitude and frequency nonstationarity of a ground motion, which is distinct from those simulated using the SIMQKE approach; (*ii*) Model parameters have been calibrated as functions of seismological variables including earthquake magnitude, closest distance and site conditions, such that synthetic ground motions can be predicted based on hazard-consistent scenarios. To be more specific, given a ground-motion time history $x(t)$, the wavelet packet coefficient is defined as Eq. (1).

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

Detailed procedure of ECSC simulation and modification technique can be referred to Huang and Wang [8]. The method provides a viable way generate synthetic ground motions that match both response spectrum and Arias intensity and its build-up with real recorded ground motions. The method is used in the current study to reproduce recorded motions in the NGA dataset to form a synthetic motion set.

2.2 ECSC, SIMQKE and NGA dataset

In this study, a total of 50 ground-motion records from three large California earthquakes are retrieved from the PEER-NGA strong-motion database [13]. Three events include the 1979 Imperial Valley earthquake, the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake. With the use of the ECSC method proposed by the author, each actual recorded motion is stochastically simulated using seismological variables (M, R, V_{s30}) associated with that record. In this way, all 50 recorded motions are “reproduced” and referred to as the ECSC simulated dataset. Additionally, another group of synthetic motion is simulated using SIMQKE proposed by Gasparini and Vanmarcke [5], which stochastically simulate ground motions compatible with a target response spectrum. The method iteratively adjusts the Fourier components of a Gaussian random process until the spectral amplitudes of simulated motion matches the target spectrum. Fig 1 shows the distribution of response spectrum of ground motions in (a) NGA subset, (b) ECSC dataset and (c) SIMQKE dataset.

Fig 2 shows one representative recording (in black line) from the NGA database and their counterparts (in blue line) from the ECSC dataset. The target motion is recorded at the Foster City station during the1989 Loma Prieta earthquake. It should be mentioned that only response spectrum and Arias intensity build-up instead of ground-motion time series are used as targets in the ECSC simulation process. It can be seen that the actual recorded and ECSC simulated motion have comparable acceleration time histories, velocity time histories and displacement time histories. Response spectra and Arias intensity build-up for each pairs of recorded and simulated ground motions match very well.

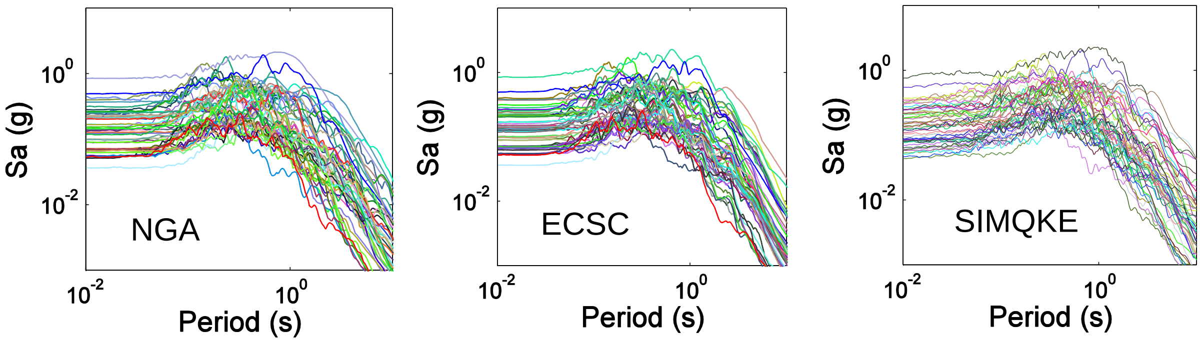

Fig. 1. Response spectra of ground motions in (a) the NGA dataset, (b) ECSC dataset and (c) SIMQKE dataset

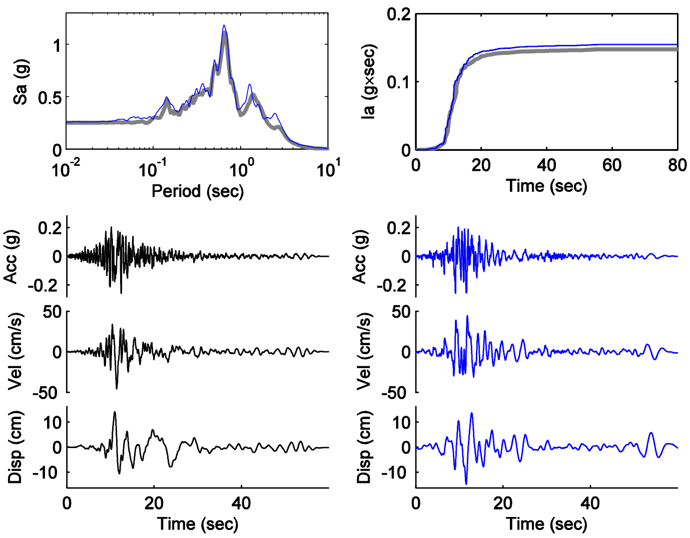

Fig. 2. Comparison of time histories, response spectra and Arias intensity build-up between NGA recorded (in black line) and ECSC simulated ground motions (in blue line)

2.3 Newmark sliding block analyses using motions from ECSC, SIMQKE and NGA datasets

Estimating seismic displacement of natural slopes is important for risk assessment of earthquake-induced landslides. In this study, the well-known Newmark sliding block analysis [14] is used to predict the seismically induced slope displacements using ECSC simulated ground-motion dataset, SIMQKE simulated dataset, compared with that computed using recorded motions in the NGA database. The Newmark model assumes sliding of a rigid block is initialized when the shaking acceleration exceeds the yield acceleration (Ky) of the sliding surface, and the block continues to slide until the relative velocity between the block and ground reaches zero. The velocity-time history of the block is then calculated by integrating the relative acceleration within that time range, and the sliding displacement is determined by integrating the velocity time history of the block. It is also worth mentioning that the yield acceleration can be determined by the strength of material and slope angle etc. [15, 16]. Fig.3 shows schematic view of Newmark sliding block system. Fig. 4 presents maximum sliding displacement calculated using ECSC simulated motions and NGA recorded motions for yield acceleration Ky from 0.01 to 0.4 g. It can be observed that the predicted Newmark sliding displacements using ECSC motions agree well with those computed using NGA recorded motions for a wide range of yield accelerations Ky = 0.01, 0.02, 0.05, 0.075, 0.1, 0.2, 0.3 and 0.4 (unit in g). The results indicate that ECSC simulation technique can obtain the same accuracy in predicting seismic sliding displacement as it does for actual recorded motions.

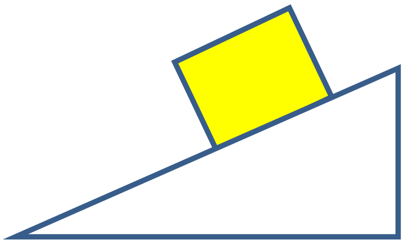

Fig. 3. Schematic view of Newmark sliding block

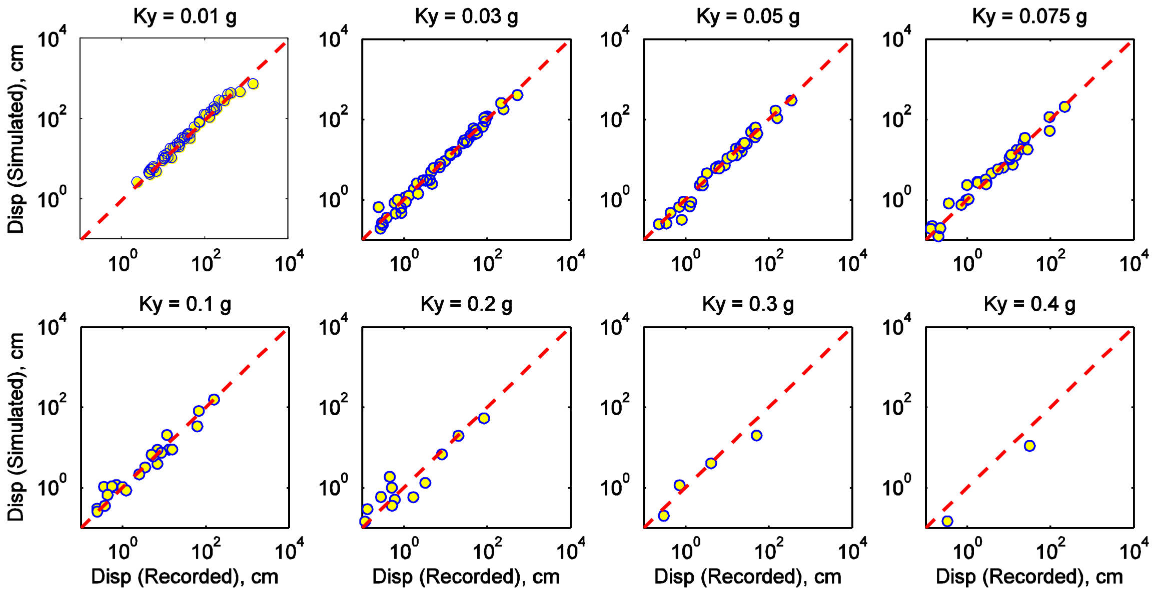

Fig. 4 Comparison of sliding displacement for yield acceleration ranging from 0.01 to 0.4 g computed using ground motions from ECSC and NGA datasets

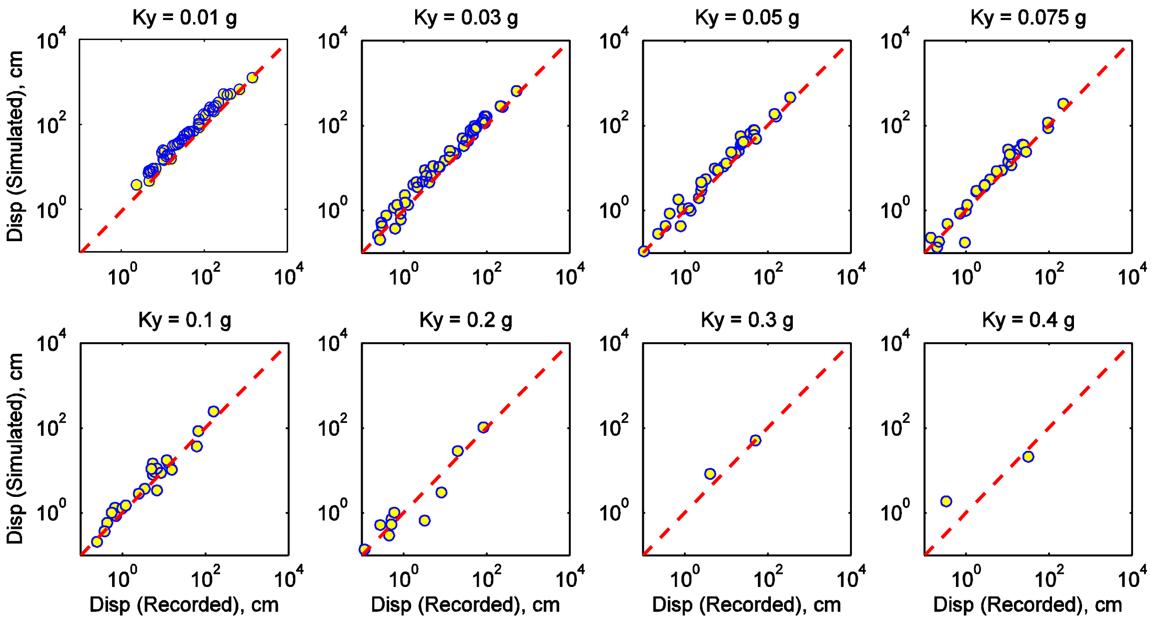

Fig. 5 Comparison of sliding displacement for yield acceleration ranging from 0.01 to 0.4 g computed using ground motions from SIMQKE and NGA datasets

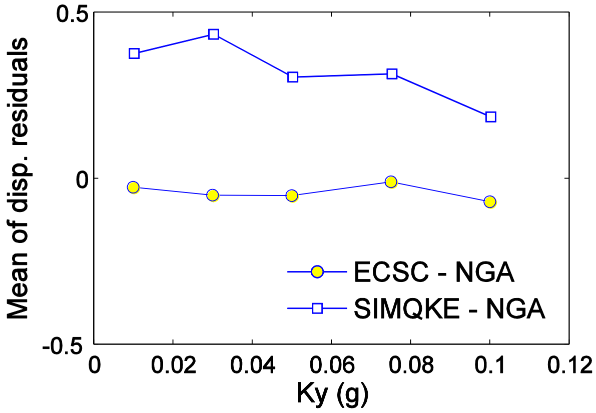

Fig. 6 Mean of displacement residuals versus yield accelerations.

Fig. 5 presents maximum sliding displacement calculated using SIMQKE simulated motions and NGA recorded motions for yield acceleration Ky from 0.01 to 0.4 g. For the cases with yield accelerations smaller than 0.1 g, the Newmark sliding displacements predicted using SIMQKE synthetic motions are 20% greater than those computed using NGA recorded motions. The reason behind is that synthetic motions generated using SIMQKE approach only match the target response spectrum, but doesn't constrain other important features such as Arias intensity, ground-motion duration and nonstationarity. Fig. 6 summarizes mean of Newmark displacement residuals computed using the two synthetic motion sets. The mean of residual displacements calculated using SIMQKE are in the range of 0.2 to 0.4, indicating a pronounced overestimation of seismic sliding displacement. On the other hand, the mean of residuals are less than 0.05 for the ECSC case when yield accelerations are across the same range (0 to 0.1g). Results in this study demonstrate that synthetic ground motions generated without constrain of above ground-motion characteristics cannot accurately predict seismic slope displacements.

2.4 Time-history analyses of a steel structure using motions from ECSC, SIMQKE and NGA sets

Time-history analyses of structures are used to estimate performance of synthetic motions under earthquake loading. We conduct one-to-one comparison of dynamic response of a steel braced structure using the ECSC simulated ground motions, SIMQKE simulated ground motions and NGA recorded motions. The structural model is 130 m in height and is established in ETABS. Fig 7 shows plan view, elevation view and 3-D view of the structure model. Time-history analyses of the steel structure are conducted using the ECSC motion set, SIMQKE motion set and the NGA dataset. The maximum floor acceleration and floor inter-story drift are recorded during the time-history analyses. Residuals r_{lnAcc} and $r_{\ln D}$ are defined to quantify the difference in the maximum floor acceleration and inter-story drift as follows,

$$r_{1,lnAcc} = ln\left(Acc_{ECSC}\right) - ln\left(Acc_{NGA}\right) \tag{2}$$

$$r_{1,\ln D} = ln\left(Disp_{ECSC}\right) - ln\left(Disp_{NGA}\right) \tag{3}$$

$$r_{2,lnAcc} = ln\left(Acc_{SIMQKE}\right) - ln\left(Acc_{NGA}\right) \tag{4}$$

$$r_{2,\ln D} = ln\left(Disp_{SIMQKE}\right) - ln\left(Disp_{NGA}\right) \tag{5}$$

where subscript 'ECSC' denotes that the structural response is computed using ECSC motions, while 'NGA' denotes the response calculated using motions from NGA subset, 'SIMQKE' represents structural response using motions from SIMQKE database.

Fig. 8 shows the mean and standard deviation of residuals for maximum floor acceleration versus story level. Specifically, Figs.8 (a) and 8 (b) denote residuals calculated using ECSC dataset against NGA dataset, while Figs. 8 (c) and 8 (d) denote residuals calculated using SIMQKE dataset against NGA dataset. On average, the mean of maximum floor acceleration residuals is well bounded within

0.1 for ECSC case as can be seen in Fig. 8 (a). The standard deviation of residuals is unchanged for different story levels, ranging from 0.12 to 0.20. On the other hand, the mean of maximum floor acceleration residuals computed using SIMQKE motions is apparently larger than that obtained from the ECSC method. It can be seen from Fig. 8 (c) that the mean of floor acceleration residuals ranges from 0 to 0.2, indicating that the SIMQKE motion set yields overestimation of structural response. Similarly, Fig. 9 shows mean and standard deviation of inter-story drift residuals obtained using the ECSC and SIMQKE datasets. The mean of residuals computed using the ECSC motions is well bounded in 0.1, indicating the method can provide overall unbiased prediction of seismic response of complex steel structures.

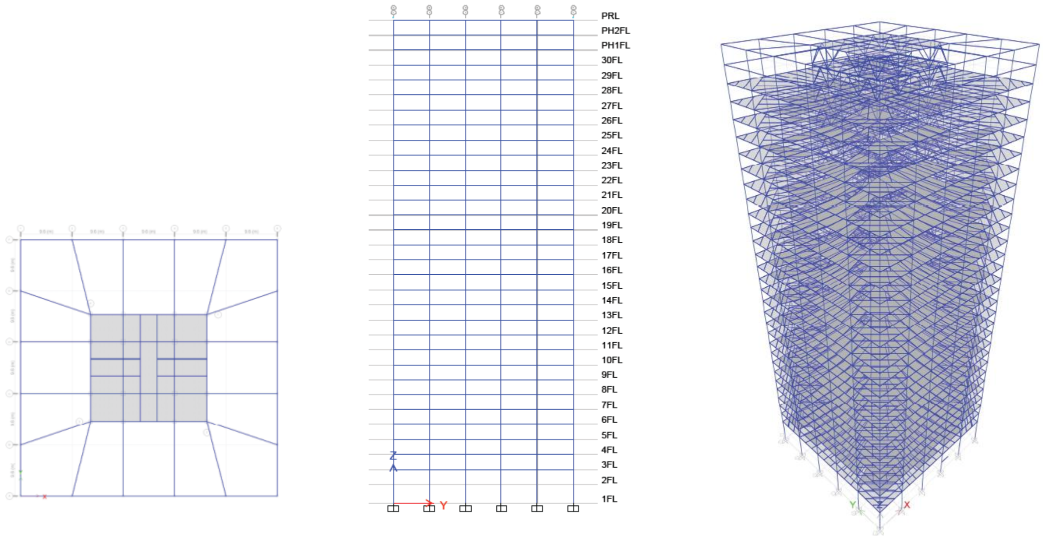

Fig. 7. (a) Plan view, (b) elevation view and (c) 3-D view of the steel structure

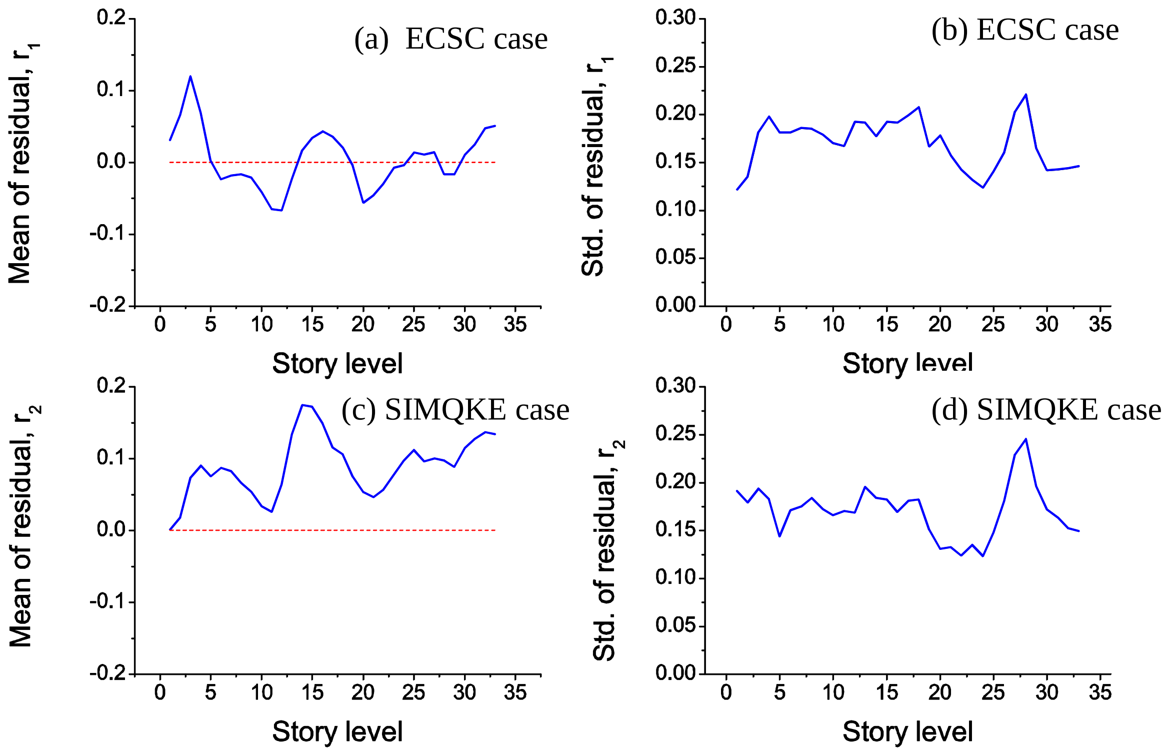

Fig. 8. (a) Mean and (b) standard deviation of residuals for maximum floor acceleration calculated using ECSC dataset versus NGA dataset; (c) Mean and (d) standard deviation of residuals for maximum floor acceleration using SIMQKE dataset versus NGA dataset

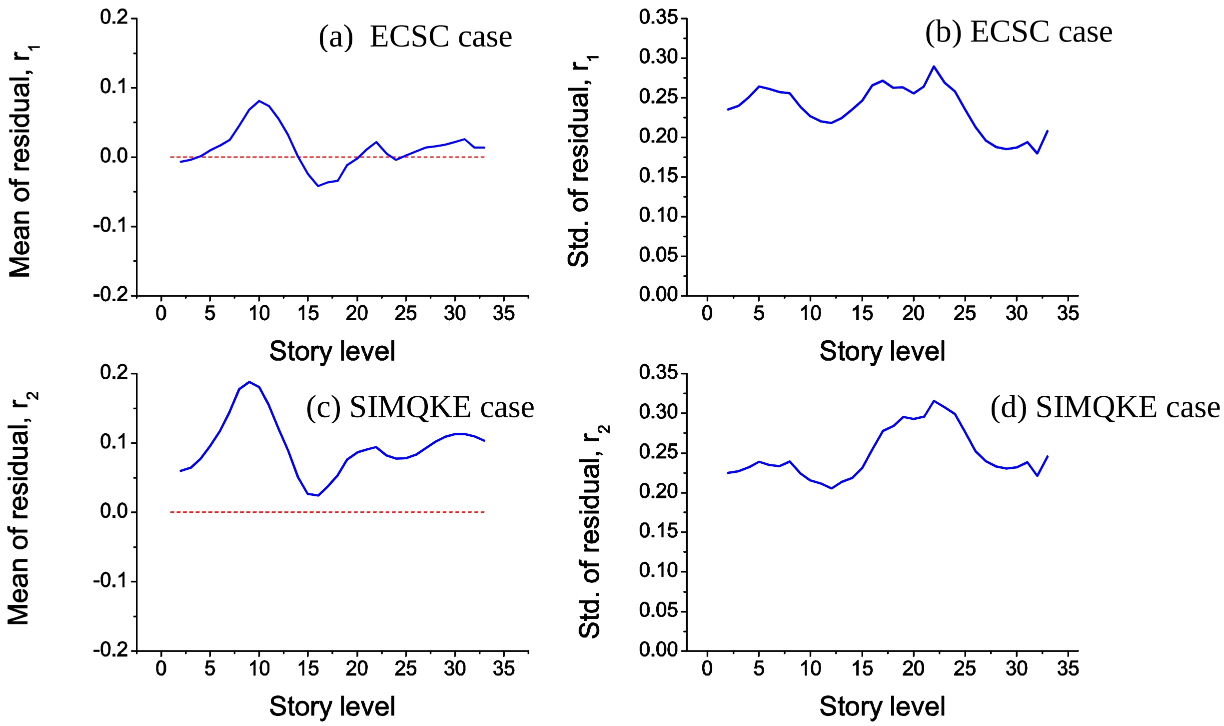

Fig. 9. (a) Mean and (b) standard deviation of residuals for maximum inter-story drift calculated using ECSC dataset versus NGA dataset; (c) Mean and (d) standard deviation of residuals for maximum inter-story drift using SIMQKE dataset versus NGA dataset

3. Conclusions

Recently, a new ground-motion simulation and modification procedure has been developed by authors that allows for generating energy-compatible and spectrum-compatible (ECSC) ground motions through wavelet-packet characterization and modification. This wavelet packet based method has a noticeable feature that ground-motion time series can be flexibly adjusted in frequency domain and time domain simultaneously, thus, response spectrum and cumulative energy can be modified iteratively. The ECSC method significantly advances traditional ground-motion modification approaches, because it generates time series that not only match target spectral accelerations, but also match other important ground motion features not considered in traditional approaches, such as the total energy and its temporal accumulation, as well as ground-motion duration.

In this study, seismic performance of synthetic motions generated using ECSC and SIMQKE approaches is evaluated using Newmark sliding blocks and a steel structure prototype. Regarding the ECSC case, the mean of residuals for both sliding displacement and inter-story drift for the steel structures are well bounded within 0.1, indicating that the method provides nonbiased estimates of both seismic slope and structural responses. More examples to validate the ECSC ground motions using other geotechnical systems can be found in Huang [12]. The method has great potential to be used in seismic assessment and time history analyses of nonlinear systems in performance-based earthquake engineering design.

Acknowledgements

The study was supported by the Hong Kong Research Grants Council (RGC) through the General Research Fund grant no. 16213615.

References

[1] Wang G, Youngs R, Power M, Li Z. Design ground motion library (DGML): an interactive tool for selecting earthquake ground motions. Earthq Spectra 2015; 31(2): 617-635.
[2] Wang G. A ground motion selection and modification method preserving characteristics and aleatory variability of scenario earthquakes. Proceedings of the 9th US national and 10th Canadian Conference on Earthquake Engineering, Toronto, July 24-29 2010.
[3] Wang G. A ground motion selection and modification method capturing response spectrum characteristics and variability of scenario earthquake. Soil Dyn Earthq Eng 2011; 31: 611-625.
[4] Youngs R, Power M, Wang G, Makdisi F, Chin CC (2007). Design ground motion library (DGML)–tool for selecting time history records for specific engineering applications. SMIP07 Seminar on Utilization of Strong-Motion Data, pp. 109-110.
[5] Gasparini DA, Vanmarcke EH. Simulated Earthquake Motions Compatible with Prescribed Response Spectra. Department of Civil Engineering: M.I.T, 1976.
[6] Wang G. Efficiency of scalar and vector intensity measures for seismic slope displacements. Frontiers of Struct Civil Eng 2012; 6(1): 44-52.
[7] Du W, Wang G. Fully probabilistic seismic displacement analysis of spatially distributed slopes using spatially correlated vector intensity measures. Earthq Eng Struct Dyn 2014; 43(5): 661-679.
[8] Huang D, Wang G. Energy-compatible and spectrum-compatible (ECSC) ground motion simulation using wavelet packets. Earthq Eng Struct Dyn 2017. DOI 10.1002/eqe.2887.
[9] Yamamoto Y and Baker JW. Stochastic model for earthquake ground motion using wavelet packets. Bull Seismol Soc Am 2013; 103(6): 3044–3056.
[10] Huang D, Wang G. Stochastic simulation of regionalized ground motions using wavelet packets and cokriging analysis. Earthq Eng Struct Dyn 2015; 44: 775-794.
[11] Huang D, Wang G. Regional-specific spatial cross-correlation model for stochastic simulation of regionalized ground-motion time histories. Bull Seismol Soc Am 2015; 105 (1): 272-284.
[12] Huang D. Stochastic simulation of spatially correlated earthquake time histories, and energy-compatible and spectrum-compatible ground motion modification using wavelet packets. Ph.D. thesis, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology; 2016.
[13] Chiou BSJ, Darragh R, Gregor N, Silva W. NGA project strong-motion database. Earthq Spectra 2008; 24: 23–44.
[14] Newmark NM. Effects of earthquakes on dams and embankments. Geotechnique 1965; 15: 139-159.
[15] Jibson RW. Regression models for estimating coseismic landslide displacement. Eng Geol 2007; 91: 209-218.
[16] Jibson RW. Methods for assessing the stability of slopes during earthquakes - A retrospective. Eng Geol 2011; 122: 43-50.