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VALIDATION OF GROUND MOTION SIMULATIONS THROUGH SPECTRAL-SHAPE AND DURATION PROXIES FOR THE NONLINEAR RESPONSE OF ENGINEERED SYSTEMS

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Abstract: We summarize the results of an ongoing study within the Southern California Earthquake Center (SCEC) Technical Activity Group (TAG) focused on Ground Motion Simulation Validation (GMSV). The aim here is to address, on a statistical basis, whether simulated ground motions for four historical earthquakes are biased in terms of median spectral-shape- and duration-related intensity measures (IMs) in comparison with real records. In particular, the study considers the Graves and Pitarka's (2010) hybrid broadband ground motion simulation methodology for the following historical events: 1979 M 6.5 Imperial Valley, 1989 M 6.8 Loma Prieta, 1992 M 7.2 Landers, and 1994 M 6.7 Northridge. We also compare the intra-event dispersion of recorded and simulated IMs. Hypothesis tests are carried out to assess the statistical significance of the results found for each IM and each event. The results from this study show that the simulation methodology matches well the recorded IMs and the observed differences are generally not statistically significant, providing confidence in using the simulation methodology for engineering application.

Introduction

Physics-based simulated (or "synthetic") ground motions (GMs) capturing complex source features (such as spatially variable slip distributions, rise-time, and rupture velocities), path effects (geometric spreading and crustal damping), and site effects (wave propagation through basins and shallow site response) provide a valuable supplement to recorded GMs, fulfilling a variety of engineering needs (Baker et al., 2014). Among engineers the general concern is that simulated records may not be equivalent to real records in estimating seismic demand, and hence, in estimating the induced damages to structures. Moreover, synthetic GMs are not yet widely available in engineering practice, especially in regions where seismogenic faults' locations and characteristics and the regional velocity structure are not established. On the other hand, in California, the recently released Southern California Earthquake Center (SCEC) Broadband Platform (Maechling et al., 2015) provides scientists and engineers with a suite of tools to compute broadband synthetic ground motions, including the effects of heterogeneous rupture propagation and nonlinear site effects.

To validate synthetic GMs, some previous and concurrent studies have employed direct (i.e., by visual inspection) comparison of observed and simulated waveforms (especially in the case of low-frequency waveforms), or comparison between median levels of observed and simulated intensity measures (IMs), particularly peak ground parameters and elastic spectral ordinates, for hybrid broadband simulation procedures (e.g., Graves and Pitarka; 2010). Star et al. (2011) have compared elastic acceleration spectral ordinates (at several periods) from simulated motions for a M_w 7.8 rupture scenario on the San Andreas Fault (two permutations with different hypocenter locations), and a M_w 7.15 Puente Hills blind thrust scenario, to median and dispersion predictions from empirical *Next-Generation Attenuation* (NGA) ground motion prediction equations (GMPEs). However, the identified discrepancies between results can indicate problems with the simulations, the GMPEs, or perhaps both. Recent studies (Galasso et al., 2012, 2013; Burks and Baker, 2014; Burks et al., 2014) have investigated whether simulated GMs are comparable to real records in terms of their nonlinear response in the domain of single degree of freedom (SDoF) systems and multiple degrees of freedom (MDoF) linear and nonlinear building systems.

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As structures' post-elastic dynamic response is fundamentally important in performance-based earthquake engineering, the study presented in this paper focuses on engineering validation of GM simulation in terms of several conventional and advanced (i.e., spectral-shape- and duration-related) IMs. Such investigation is a proxy for assessing the similarity of nonlinear structural response and damage potential of simulated and recorded motions for many real structural types. In particular, the considered spectral-shape- and duration-related IMs are derived for different structural periods considering Graves and Pitarka's (2010) hybrid broadband simulation methodology for four historical Californian earthquakes (see *Description of synthetic and real ground motion datasets*). In fact, past events provide an important opportunity to test the ability to use hybrid broadband simulation to generate synthetic GMs consistent with those observed. In a broader perspective, the hybrid broadband simulation provides a complete prescription for simulating motions for future earthquakes, including extrapolation to those beyond the magnitude range considered in the current set of validation events (Graves and Aagaard, 2011).

The aim here is to address, on a statistical basis, whether simulated GMs are systematically biased in terms of their average spectral-shape- and duration-related characteristics in comparison with real records. We also look at the dispersion (i.e., intra-event variability) of the selected IMs for recorded and simulated GMs. Hypothesis tests are carried out to quantitatively assess the results' statistical significance.

The results from this study highlight the similarities and differences between synthetic and real records. These similarities should provide confidence in using the simulation methodology for engineering application, while the discrepancies, if statistically significant, should help in improving the generation of synthetic records.

Description of synthetic and real ground motion datasets

Graves and Pitarka (2010) developed a hybrid broadband (0-10 Hz) GM simulation methodology which combines a physics-based deterministic approach at low frequency ($f \leq 1$ Hz; i.e., $T \geq 1$s) with a semistochastic approach at high frequency ($f > 1$ Hz; i.e., $T < 1$s). The low- and high-frequency waveforms are computed separately and then combined to produce a single time history through a matching filter. At frequencies below 1 Hz, the methodology contains a theoretically rigorous representation of fault rupture and wave propagation effects and attempts to reproduce recorded GM waveforms and amplitudes. At frequencies above 1 Hz, waveforms are simulated using a stochastic representation of source radiation combined with a simplified theoretical representation of wave propagation and scattering effects. The use of different simulation approaches for the different frequency bands results from the seismological observation that source radiation and wave propagation effects tend to become stochastic at frequencies of about 1 Hz and higher, primarily reflecting the relative lack of knowledge about these phenomena's details at higher frequencies. For both short and long periods, the effect of relatively shallow site conditions, as represented by shear wave velocity in the upper 30 m (V_{s30}) is accounted for using Campbell and Bozorgnia's (2008) empirical site amplification model.

The present study uses four historical earthquakes modeled by Graves and Pitarka (2010): 1979 M 6.5 Imperial Valley, 1989 M 6.8 Loma Prieta, 1992 M 7.2 Landers, and 1994 M 6.7 Northridge. The only earthquake-specific input parameters used in the simulation process are the seismic moment, the overall fault dimensions and geometry, the hypocenter location, and a smoothed representation of the final slip distribution. All other required source parameters (e.g., rupture propagation time, rise time, slip function, and fine-scale slip heterogeneity) are developed using the scaling relations presented by Graves and Pitarka (2010). For each simulated event, the model region covers a wide area surrounding the fault, including many strong motion recording sites available in the NGA database: 33 for Imperial Valley, 71 for Loma Prieta, 23 for Landers, and 133 for Northridge. These sites are shown with triangles in Figure 1.

This study uses a limited number of sites mentioned in the previous paragraph, considering only those that have real recordings with a usable bandwidth larger than 0.1s-8s. This limitation yields a total of 126 sites for the entire study. These sites are marked with filled triangles in Figure 1. Such large bandwidth for recorded motions provides a justifiable means of covering a good range of nonlinear structural systems where nonlinear response is sensitive to spectral ordinates beyond the fundamental period.

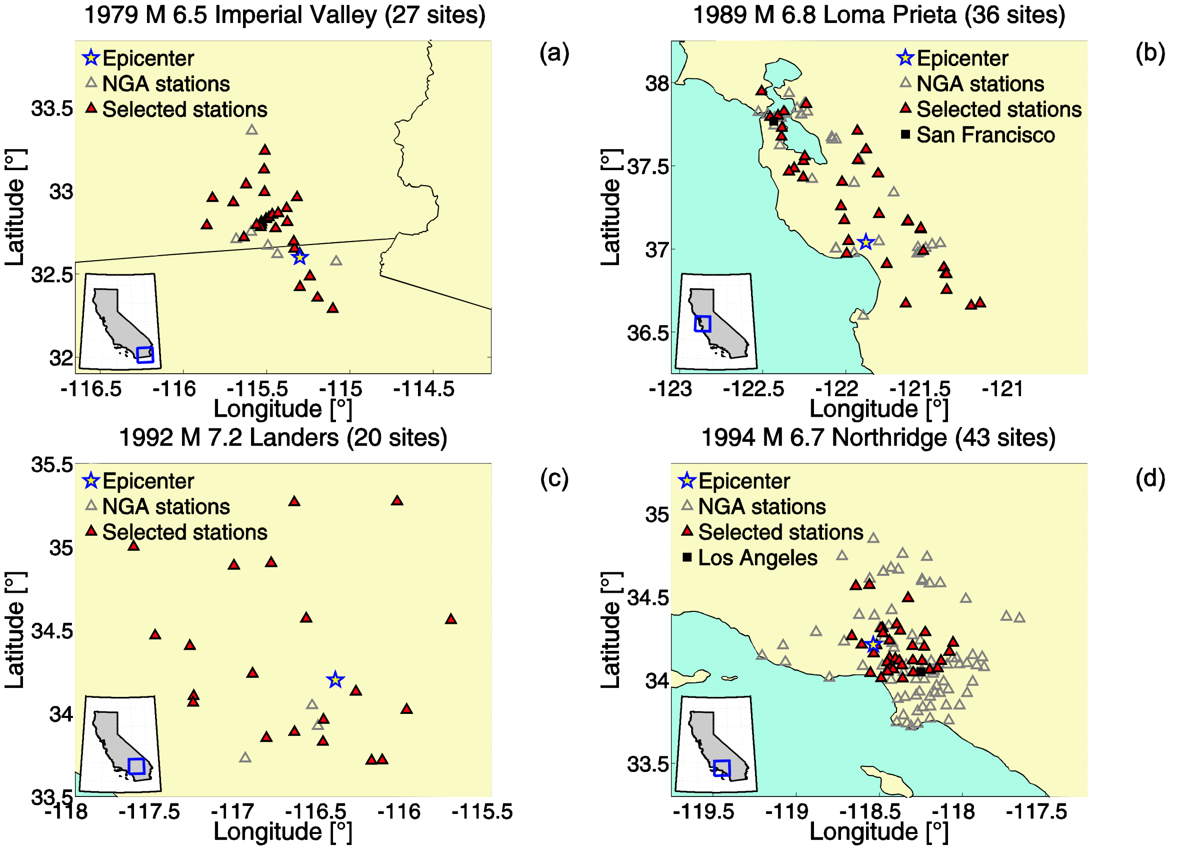

Figure 1. Maps of the earthquakes considered. The star is the epicenter and the triangles are the recording stations in the NGA database for which the simulations are available. The filled triangles are the recording stations considered in this study. San Francisco (b) and Los Angeles (d) are also indicated on the map (squares).

Description of considered intensity measures

An IM is a scalar GM parameter, which is considered to be representative of the earthquake damage potential with respect to a specific structure. Conventional IMs, including the peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and spectral (pseudo-) acceleration at the initial fundamental period (for a damping ratio of 5%), $S_a(T_1)$, are the most commonly used IMs. In general, PGA and $S_a(T_1)$ poorly predict the structural response of mid- to high-rise moment resisting frames (MRFs), although the latter IM sufficiently captures the elastic behaviour of first-mode dominated MDoF systems, especially in the case of low to moderate fundamental periods (Shome *et al.*, 1998). However, the behaviour of highly nonlinear structures or structures dominated by higher-mode periods (less than T_1) are not very well represented by utilising $S_a(T_1)$ due to the lack of information on the spectral-shape provided by this IM. Therefore, it is becoming essential implementing advanced IMs that account for the elongated periods and/or consider nonlinear demand dependent structural parameters. Giovenale et al. (2004) and Buratti (2012) amongst others have investigated the adequacy of numerous advanced scalar IMs measures that take into consideration the aforementioned parameters.

The first advanced scalar IM considered in this study is S_a^c (proposed by Cordova et al., 2000), which utilises spectral shape information (period elongation), and is expressed as:

$$S_a^c = S_a(T_1)\left[\frac{S_a(cT_1)}{S_a(T_1)}\right]^{\alpha} \tag{1}$$

where *c* and α are coefficients assumed to be *c* = 2 and α = 0.5 respectively, based on the calibration carried out by the authors in the original study.

Bojórquez and Iervolino (2011) also proposed the advanced scalar IM, I_{N_p}, which is based on $S_a(T_1)$ and the parameter N_p, defined as:

$$I_{N_p} = S_a(T_1)N_p^{\alpha} \tag{2}$$

where α parameter is assumed to be α = 0.4 based on the tests conducted by the authors, and N_p is defined as:

$$N_p = \frac{S_{a,avg}(T_1,\ldots,T_N)}{S_a(T_1)} = \frac{\left[\prod_i^N S_a(T_i)\right]^{1/N}}{S_a(T_1)} \tag{3}$$

T_N corresponds to the maximum period of interest and lays within a range of 2 and 2.5*T1*, as suggested by the authors.

In this study, the advanced IMs described above are computed for four different fundamental periods T_1: 0.5s, 1s, 2s and 4s. For the N_p computation, 3 periods are considered: T_1, $1.5T_1$ and $2T_1$.

Integral parameters, as the *Arias intensity* or *significant ground motion duration*, are possible IMs, but they are considered to be related more to the cyclic energy dissipation rather than to the peak structural response. In fact, some studies (e.g., Iervolino et al., 2006) investigated how ground motion duration-related parameters affect nonlinear structural response. It was found that, generally, spectral ordinates are *sufficient* (i.e., duration does not add much information) if one is interested in the ductility demand, while duration-related measures do play a role only if the hysteretic structural response is that to assess; i.e., in those cases in which the cumulative damage potential of the earthquake is of concern. Therefore, the engineering validation of simulated GM in terms of duration-related parameters is also of significant importance.

In particular, Arias intensity, I_A (Arias, 1970) is one of the most commonly used integral IM and is defined by the integral of ground acceleration as:

$$I_A = \frac{\pi}{2g}\int_0^{t_E} a^2(t)dt \tag{4}$$

where *a*(*t*) is the acceleration time history and t_E is the complete duration of the ground motion. The term duration can also be used to identify only the portion of a record in which the GM amplitude can potentially cause damage to engineering and geotechnical structures. Several definitions are proposed to this aim; the most commonly used one is the *significant duration*, introduced by Trifunac and Brady (1975) on the base of the study by Husid (1969), is defined as the time interval over which the integral of the square of the ground acceleration (Husid plot) is within a given range of its total value. Usually this range is between 5 and 95% (as in this study), denoted as $D_{a5\text{-}95}$, or between 5 and 75%.

Finally, Consenza and Manfredi (1997) introduced the I_D- factor defined in Equation (5) that has proven to be a good proxy for cyclic structural response (Manfredi, 2001):

$$I_D = \frac{\int_0^{t_E} a^2(t)dt}{PGAPGV} \tag{5}$$

In the above equation, $a(t)$ is the acceleration time history, t_E is the complete duration of the ground motion and PGA and PGV are the peak ground acceleration and velocity respectively.

Methodology

All GMs (recorded and simulated) selected for each earthquake event are used as input to compute the selected IMs described in the above section. Only the horizontal components of GMs (i.e., north-south [NS], and east-west [EW]) are used, while the vertical component is neglected. The IMs for the two horizontal components at each station are computed and then combined into an “average” value using the geometric mean. Parametric hypothesis tests are performed to quantitatively assess the statistical significance of differences found in terms of different IMs (for each oscillation period) for recorded and simulated GMs. Following the approach of Galasso et al. (2012, 2013), hypothesis tests are performed assuming a lognormal distribution for each IM of interest. These distribution assumptions were checked with the Shapiro-Wilk (Shapiro and Wilk, 1965) test and could not be rejected, at a 95% significance level. The null hypothesis (H_o) is that the mean difference between paired IMs, recorded and simulated, is zero. When the mean difference is zero, the means of the two groups must also be equal. To address this aim, we selected a paired sample *t*-test (e.g., Mood et al., 1974). The employed test statistic is reported in Equation (6), in which $\bar{d}$ is the mean difference between the two samples, s_d is the standard deviation of the differences, and n is the sample size for each earthquake scenario.

$$t = \frac{\bar{d}}{s_d / \sqrt{n}} \tag{6}$$

Under the null hypothesis, the statistic of Equation (6) follows a *t*-distribution with $n - 1$ degrees of freedom.

A similar parametric hypothesis test, the *F*-test (e.g., Mood et al., 1974) for normally distributed data, has been performed to compare variances for each IM (in logs terms), for the two datasets (recorded and simulated) corresponding to each earthquake; in this case, the null hypothesis is that the variance of each IM for simulated GMs is equal to the variance from recorded GMs.

Results and discussions

To summarize the results of the hypothesis tests and draw conclusions, the *p*-values of the hypothesis tests are reported in Tables 1-3 for each IM and earthquake event. More specifically, Tables 1 and 2 present the *p*-values for the paired sample *t*-test and the *F*-test respectively for the spectral-shape proxies while Table 3 presents the *p*-values for the paired sample *t*-test and the *F*-test for the duration-related proxies.

For the hypothesis tests yielding a *p*-value less than 0.01 (1%), there is strong evidence to reject the null hypothesis and thus, the differences in the IMs (or their intra-event variability) from simulations and real records are statistically significant. These cases are highlighted with the red colour in Tables 1-3.

Table 1. *p*-values for the paired *t*-test for spectral-shape-related IMs.

IM	Event	T_1 = 0.5s	T_1 = 1s	T_1 = 2s	T_1 = 4s
$S_a(T_1)$	Landers	0.8886	0.9032	0.0138	0.0648
	Loma Prieta	0.9963	0.0216	**0.0001**	0.0821
	Imperial Valley	0.5203	0.8714	0.4583	0.8459
	Northridge	0.1180	0.9958	0.0421	0.5337
S_a^c	Landers	0.9944	0.1745	0.0139	0.0908
	Loma Prieta	0.1566	0.3659	**0.0005**	0.8247
	Imperial Valley	0.6897	0.6300	0.7456	0.6844
	Northridge	0.4132	0.3369	0.1385	0.5829
I_{N_p}	Landers	0.9136	0.5301	0.0178	0.0736
	Loma Prieta	0.4976	0.2819	**0.0001**	0.3758
	Imperial Valley	0.5399	0.7480	0.5814	0.9954
	Northridge	0.1645	0.6317	0.0621	0.4979

Table 2. *p*-values for the *F*-test for spectral-shape-related IMs.

IM	Event	T_1 = 0.5s	T_1 = 1s	T_1 = 2s	T_1 = 4s
$S_a(T_1)$	Landers	0.5322	0.7148	**0.0018**	0.7922
	Loma Prieta	0.2286	0.0341	**0.0001**	0.5449
	Imperial Valley	0.9503	0.0199	**0.0000**	0.4505
	Northridge	0.0162	0.5167	0.1791	0.5550
S_a^c	Landers	0.7254	0.0416	0.0622	0.3308
	Loma Prieta	0.4053	**0.0004**	0.0748	0.3527
	Imperial Valley	0.1355	**0.0008**	0.0129	0.1457
	Northridge	0.1582	0.5998	0.5381	0.4823
I_{N_p}	Landers	0.7825	0.2430	**0.0051**	0.7955
	Loma Prieta	0.5010	**0.0032**	**0.0044**	0.4735
	Imperial Valley	0.5564	**0.0027**	**0.0009**	0.3552
	Northridge	0.0269	0.9891	0.4094	0.4613

For the hypothesis tests yielding a *p*-value greater than 0.01 (1%) and smaller than 0.05 (5%) there is some evidence to reject the null hypothesis; these cases are highlighted with the orange colour in Tables 1-3. Lastly, for *p*-values greater than 0.05 or 5%, there is not sufficient evidence to reject the null hypothesis, meaning that the differences in the IMs or their intra-event variability from simulations and real records are not statistically significant. These cases are highlighted with the green colour in Tables 1-3.

Based on these Tables, tests have shown a statistical significance in the bias of the shape related IMs estimation using simulated records, only at periods around 2 s for Landers and Loma Prieta events. The differences in this period range reveal the large differences in both absolute and relative amplitudes (i.e., the shape) of the elastic response for the Loma Prieta and Landers events as discussed in Galasso et al. 2012. For the duration-related IMs, the results show a statistical significance of the differences in terms of significant duration $D_{a5\text{-}95}$ for most earthquake events. The differences in the intra-event variability estimated using simulated and real GMs appears statistically significant for the case of spectral-shape-related IMs between 1 and 2 s, whereas for the duration-related IMs, the variances are not significantly different with some sparse rejections in terms of I_D and $D_{a5\text{-}95}$.

Table 3. *p*-values for the paired *t*-test and *F*-test for duration-related IMs.

IM	Event	*p*-value *t*-test	*p*-value *F*-test
I_A	Landers	0.3113	0.2588
	Loma Prieta	0.4433	0.0909
	Imperial Valley	0.9169	0.0104
	Northridge	0.6682	0.8569
I_D	Landers	0.1496	0.0450
	Loma Prieta	0.8849	0.4911
	Imperial Valley	0.5710	0.8749
	Northridge	0.0302	**6.87E-07**
D_{a5-95}	Landers	**0.0037**	0.3118
	Loma Prieta	**0.0086**	**0.0080**
	Imperial Valley	0.1333	0.1647
	Northridge	0.0497	0.2337

Conclusions

The design of new structures or assessment of existing ones may be complicated by the inherent rareness or total absence of suitable real (i.e., recorded) accelerograms for the earthquake scenarios that dominate the seismic hazard at a given site. Therefore, hybrid broadband synthetic records may be an attractive alternative as input to nonlinear dynamic analysis, if their structural response equivalency to real GMs with same seismological features is proven. The present study had two main objectives: 1) to validate Graves and Pitarka's (2010) hybrid broadband simulation methodology by statistically examining spectral-shape- and duration-related IMs; and 2) to identify situations where the simulated and recorded GMs produce different characteristics to guide further areas of the simulations where refinement is needed. Results of this study show, in the context of the IMs studied, that the simulation methodology matches well the IMs and their variability produced by recorded GMs and that the observed differences generally are not statistically significant across the considered structural periods. This paper's generally favorable comparisons between simulations and recorded data lend support to the simulation methodology's predictive capabilities, and are directly relevant to the engineering community, who may use the simulation methodology with confidence. These results may also provide feedback for seismologists who generate simulated GMs for engineering applications.

REFERENCES

Arias A (1970) *A measure of earthquake intensity, in Seismic Design for Nuclear Power Plants*, edited by R. Hansen, MIT Press, Cambridge, MA

Baker JW, Luco N, Abrahamson NA, Graves RW, Maechling PJ, Olse KB (2014) *Engineering Uses of Physics-Based Ground Motion Simulations*, Proceedings of the 10th US National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, Anchorage, Alaska, 21-25 July

Bojórquez E, Iervolino I (2011) Spectral shape proxies and nonlinear structural response, *Soil Dynamics and Earthquake Engineering*, 31(7): 996-1008

Buratti N (2012) *A comparison of the performances of various ground–motion intensity measures*, Proceedings of the 15th World Conference on Earthquake Engineering. Lisbon, 24-28 September

Burks LS and Baker JW (2014) Validation of ground-motion simulations through simple proxies for the response of engineered systems, *Bulletin of the Seismological Society of America*, 104(4): 1930-1946

Burks LS, Zimmerman RB, Baker JW (2014) Evaluation of Hybrid Broadband Ground Motion Simulations for Response History Analysis and Design, *Earthquake Spectra (in press)*

Campbell KW, Bozorgnia Y (2008) NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, *Earthquake Spectra*, 24(1): 139–171

Cordova PP, Deierlein GG, Mehanny SS, Cornell CA (2000) *Development of a two-parameter seismic intensity measure and probabilistic assessment procedure*, Proceedings of the 2nd US–Japan Workshop on Performance-Based Earthquake Engineering for Reinforced Concrete Building Structures , Sapporo, Japan, 11–13 September

Cosenza E, Manfredi G (1997) *The improvement of the seismic-resistant design for existing and new structures using damage criteria*, In Seismic Design Methodologies for the Next Generation of Codes, Fajfar P, Krawinkler H (eds), Balkema: Rotterdam, 119 –130

Galasso C, Zareian F, Iervolino I, Graves RW (2012) Validation of ground-motion simulations for historical events using SDoF systems, *Bulletin of the Seismological Society of America*, 102(6): 2727-2740

Galasso C, Zhong P, Zareian F, Iervolino I, Graves RW (2013) Validation of ground-motion simulations for historical events using MDoF systems, *Earthquake Engineering and Structural Dynamics*, 42(9): 1395-1412

Giovenale P, Cornell AC, Esteva L (2004) Comparing the adequacy of alternative ground motion intensity measures for the estimation of structural responses, *Earthquake Engineering and Structural Dynamics*, 33(8): 951–979

Graves RW, Pitarka A (2010) Broadband ground-motion simulation using a hybrid approach, *Bulletin of the Seismological Society of America*, 100(5A): 2095-2123

Graves RW, and Aagaard BT (2011) Testing long-period ground-motion simulations of scenario earthquakes using the M w 7.2 El Mayor-Cucapah mainshock; evaluation of finite-fault rupture characterization and 3D seismic velocity models, *Bulletin of the Seismological Society of America*, 101(2): 895-907

Husid LR (1969) *Características de terremotos, Análisis general, Revista del IDIEM 8*, Santiago del Chile, 21–42

Iervolino I, Manfredi G, Cosenza E (2006) Ground-motion duration effects on nonlinear seismic response, *Earthquake Engineering and Structural Dynamics*, 35(1): 21-38

Maechling PJ, Silva F, Callaghan S, Jordan TH (2015) SCEC Broadband Platform: System Architecture and Software Implementation, *Seismological Research Letters*, 86(1): 27-38

Manfredi G (2001) Evaluation of seismic energy demand, *Earthquake Engineering and Structural Dynamics*, 30(4): 485-499

Mood MA, Graybill FA, Boes DC (1974) *Introduction to the Theory of Statistics*, 3rd Ed., McGraw-Hill, New York

Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples), *Biometrika*, 52(3-4): 591-611

Shome N, Cornell CA, Bazzurro P, Carballo JE (1998) Earthquakes, records, and nonlinear responses, *Earthquake Spectra*; 14(3): 469–500

Star L, Stewart JP, Graves RW (2011) Comparison of ground motions from hybrid simulations to NGA prediction equations, *Earthquake Spectra*, 27(2): 331-350

Trifunac MD, Brady AG (1975) A study on the duration of strong earthquake ground motion, *Bulletin of the Seismological Society of America*, 65: 581– 626