SITE RESPONSE MODELING VARIABILITY IN "RUPTURE-TO-RAFTERS" GROUND MOTION SIMULATIONS

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ABSTRACT:

In this paper, we combine downhole observations and broadband ground motion synthetics evaluated at three downhole array sites in the Los Angeles Basin, to investigate the ground surface response and structural performance variability introduced in the predictions by the selection of the site response analysis methodology. For this purpose, we combine regional velocity and attenuation crustal profiles with available near-surface geotechnical data at the three sites. Broadband ground motion simulations are next conducted for rupture scenarios of weak, medium and large magnitude events (M = 3.5~7.5), and three component seismograms are computed on a surface station grid of epicentral distances 2km~75km. Elastic, equivalent linear and nonlinear site response analyses are then evaluated, and the modeling site response variability is estimated by means of the COV (coefficient of variation) of site amplification factors. A frequency index is developed, which combined with the ground motion intensity may be used as a quantitative criterion that decribes the site and ground motion conditions where the alternative site response methodologies show large variability of predictions. High COV in predictions implies strong sensitivity of the computed motion to the selection of the site response model, and indicates that realistic predictions may be achieved only by means of incremental nonlinear analyses that deviate significantly from widely employed approximate or empirical methodologies. Finally, a series of inelastic SDOF (single-degree-of-freedom) oscillators are subjected to the ensemble of ground motion predictions obtained via the alternative site response methodologies. The bias and uncertainty introduced in the structural response predictions is evaluated as a function of the frequency criteria proposed in this work, to investigate the propagation of site response modeling variability to the assessment of structural performance measures in rupture-to-rafters simulations. Results show that large sensitivity in the selection of site response methodology yields high bias and uncertainty in the assessment of the inelastic displacement ratio for nonlinear structural response predictions, indicating the efficiency of the proposed criteria for the optimal selection of site response analysis.

KEYWORDS: site response, ground motion, modeling uncertainty, inelastic structure response

1 INTRODUCTION

The widespread implementation of performance-based design (PBD) procedures in current engineering practice has underlined the need for the fields of engineering and seismology to become more rationally linked. To that end, advancements in the representation of dynamic source rupture models such as detailed descriptions of heterogeneous friction-based slip functions on fault surfaces, and efforts on the development of detailed 3D crustal velocity and fault system models for seismically active regions have enabled high spatio-temporal resolution of earthquake ground motion predictions. As a result, broadband ground motion models can nowadays predict realistic seismic waveforms over the engineering application range (<10Hz), and their implementation in physics-based earthquake simulations from-rupture-to-rafters is currently transforming basic and applied earthquake science into an interdisciplinary, system-level research field where rupture models are integrated with discipline-based observations in seismology and engineering.

"Rupture-to-rafters" ground motion predictions for engineering applications, however, require continuous representation of the physics, and at the "interface" of the two disciplines, strong motion site response simulations are often involved: (i) in engineering practice procedures for the design of earthquake-resistant structures on soft soils; (ii) in the development of synthetic-based attenuation relations for stable continental, low seismicity regions for implementation in probabilistic seismic hazard analyses (PSHA) in absence of observations, (iii) in hybrid attenuation relations where ground motion recordings are integrated with predictions for regression analyses to be conducted on statistically significant datasets that include rare, damaging events; and (iv) in the development of time-history suites for input into nonlinear structural response analyses to design level motions, typically associated with permanent ground deformations at soft sites (Baturay and Stewart, 2003; Cramer, 2006; Kwok et al., 2006; Stewart et al., 2002).

Realistic predictions of the response of soft soils to strong ground motion in turn, may only be achieved via nonlinear analyses, which require large computational cost and effort to develop the required input model parameters. Currently, the lack of quantitative guidelines for the efficient integration of nonlinear models in large-scale simulations from source-to-structure, and the limited number of well-documented validation studies that illustrate the reduced uncertainty/bias in ground motion/structural response predictions achieved by using nonlinear soil response analyses relative to empirical methodologies, hinder their integration in ground motion models. Instead, approximate methods deeply rooted in the earthquake engineering design community still dominate the state-of-the-art in PSHA, while site effects in seismologically-based earthquake scenario simulations are for the most part accounted via empirical intensity-dependent amplification factors derived from regression analyses of ground motion observations.

The critical role of soil response predictions in physics-based earthquake simulations necessitates the development of a unified methodology to allow their interdisciplinary implementation. We here illustrate the significance of nonlinear site response methodology selection, and its impact on the prediction of nonlinear structural performance measures in "rupture-to-rafters" simulations, by integrating downhole array observations and synthetic predictions of strong motion site response at three sites in the Los Angeles Basin. Furthermore, we quantify the variability propagation of nonlinear analyses procedures to ground motion intensity measure estimates (IM's), and nonlinear structural response characteristics for PBD engineering implementation. Given the limited number of site conditions investigated, and the lack of design-level observations, site and ground motion criteria identified here to allow quantitative description of the conditions under which the cost and effort associated with fully nonlinear site response analyses should be credited are tentative. Validation of the criteria for implementation in rupture-to-rafters simulations would require a statistically significant dataset of site conditions, synthetic rupture scenarios and design-level observations investigated along the lines of the analysis framework described in the ensuing.

2 STRONG GROUND MOTION SITE RESPONSE MODELING UNCERTAINTY

Nonlinear models have been integrated in regional hazard studies, and their effects on PSHA's have been quantified. Among others, Park and Hashash (2004, 2005) developed a procedure that directly accounts for nonlinear site effects by conducting wave propagation analyses (PSHA-NL). Cramer et al (2004) generated a suite of seismic hazard maps for Memphis, TN, that accounted for site effects related to the sediments in the Mississippi Embayment (ME); their response was simulated by approximate and incremental nonlinear analyses, and the prediction scatter was found to arise from uncertainties in the soil properties, and the choice of nonlinear code. Successively, Cramer (2006) combined the methodology above with the reference profile approach of Toro and Silva (2001) to better estimate seismic hazard in the ME. The added uncertainty in site amplification estimates due to the choice of site response model was of the order of 20–50% for PSHA.

Assimaki et al. (2008) computed the variability of ground response predictions introduced by the site response methodology implemented, at three downhole array sites in the Los Angeles Basin. For this purpose, they combined a limited dataset of surface and downhole strong motion observations with broadband ground motion synthetics, computed for the regional geology structure and fault system and the geotechnical characteristics of the site-specific near-surface soil layers. Three component ground surface seismograms were evaluated for multiple rupture scenarios at a wide range of epicentral distances by means of a broadband dynamic rupture finite-source model assuming reference site conditions (soft rock) in the near-surface. Ground surface synthetics were next deconvolved to the incident motion at engineering bedrock depth, and propagated back to ground surface by means of three alternative methods: elastic, equivalent linear and nonlinear site response analysis. The modeling site response uncertainty was reported by means of the COV of site amplification factor predictions by the ensemble of models. A frequency index was developed to describe the alignment of resonant site characteristics to the incident ground motion frequency content and thus quantify the amplification potential at a given site to a given incident seismic wave. This frequency was originally defined as the ratio of the central frequency of ground motion spectrum to the central frequency of the elastic site response transfer function (Assimaki et al, 2008). The frequency index was next combined with the peak ground acceleration (PGA) on reference site ground surface as measure of motion intensity, and both measures were used to describe the site and ground motion conditions where the alternative site response methodologies show large variability of predictions. High COV in predictions implied strong sensitivity of the computed motion to the selection of the site response model, and indicated that realistic predictions would be achieved only by means of incremental nonlinear analyses that were shown to deviate significantly from widely employed approximate or empirical methodologies results.

We here replaced the originally formulated frequency index described above by the normalized cross-correlation between the elastic function of the site and the Fourier amplitude spectrum of the incident motion, and plotted results of the work by Assimaki et al (2008) using the new, more effective index. Using the new frequency index and the PGA on rock-outcrop of ground motion predictions, we next evaluated the response of a series of inelastic SDOF (single-degree-of-freedom) oscillators to the ensemble of ground motion predictions obtained via the alternative site response methodologies. The bias and uncertainty introduced in the structural response predictions was evaluated as a function of the site and ground motion criteria proposed in this work, to investigate the propagation of site response modeling variability to the assessment of structural performance measures in rupture-to-rafters simulations. Results showed that large sensitivity in the selection of site response methodology yields high bias and dispersion in the assessment of the inelastic structural response predictions, indicating the efficiency of the proposed criteria for the optimal selection of site response analysis integrated in rupture-to-rafters simulations. This study is the sequence of our previous work on modelling uncertainty in site response analysis for quantification of nonlinearity susceptibility of soil formations in broadband ground motion simulations. Therefore, the readers are referred to Assimaki et al (2008) for detailed description of the site conditions, ground motion synthetics computation, and empirical and incremental nonlinear methodologies and implementation description, while only the basic characteristics of sites and ground motion synthetics used here are described in the ensuing for completeness of the presented results.

2.1 Site conditions at three downhole arrays in the Los Angeles Basin and ground motion synthetics

Figure 1 depicts the locations of the three instrumented geotechnical downhole arrays in Southern California investigated in this study. Geotechnical data available at these stations comprise downhole and suspension logging shear wave velocity profiles (V_s), as well as scarce laboratory resonant column modulus degradation and damping curves (Anderson, 2003). The seismic waveform inversion algorithm developed by Assimaki et al (2006) was employed for the refinement of the coarse description of the V_s profile with depth and the estimation of the attenuation (low-strain damping) and density profiles using low-amplitude seismogram recordings. The resulting shear wave velocity (V_s), attenuation (Q=1/2ξ, where ξ is the material damping) and density profiles (ρ) are illustrated in **Figure 1b**; the available on-site geotechnical investigation data of V_s suspension logging at the corresponding sites. One-dimensional crustal compressional velocity (V_p), shear velocity (V_s) and density models (ρ) were next extracted from the 3D Southern California Community Velocity Model IV (SCEC CVM IV: http://www.data.scec.org/3Dvelocity/) at the locations of the three arrays (**Figure 1c**).

The crustal models extracted from SCEC CVM IV were successively used for the simulation of broadband ground motion synthetics. More specifically, due to the scarcity of recordings at the stations of interest, strong ground motion synthetics were computed for multiple rupture scenarios over a wide range of epicentral distances to develop a statistically significant dataset of ground motion waveforms, which will allowing a sound assessment of the site response modelling variability and its propagation to structural response predictions. In particular, broadband ground motion time-histories were here simulated for multiple strike-slip fault rupture scenarios over a 100×100km^2 square grid (**Figure 2a**) for medium and large magnitude events (M_w = 3.5 ~ 7.5), corresponding to a wide spectrum of ground motion intensity and frequency characteristics. Broadband ground motion time-histories were computed by means of a dynamic rupture source model referred to as the hybrid low-/high-frequency approach with correlated source parameters (Liu et al, 2006). In accordance to the formulation of this model, low frequency synthetics (<1 Hz) were computed for a deterministic 3D velocity structure using a finite-difference method, while broadband components (1<f<10Hz) were computed for a 1D heterogeneous velocity model using a frequency-wave-number method. A typical realization of the random distribution of slip, rupture velocity and stress drop on a 1D crustal model strike-slip discontinuity rupturing 2km below the ground surface is shown in **Figure 2b**.

2.2 Nonlinearity susceptibility of soil profiles to strong motion via site response modelling uncertainty

Broadband ground motion synthetics were initially computed by means of linear elastic analyses in the near surface of soft rock (reference site conditions) where nonlinear effects were anticipated to be minimal during strong ground shaking. Successively, ground surface motions were deconvolved to the level of the lowermost downhole instrument (on the order of 100m deep), where the role of soil nonlinearity is assumed to be insignificant. Conditioned on this assumption, the incident motion computed at that depth is affected purely by source and path effects. Successively, the estimated incident motions were propagated to the surface by means of the alternative approximate and elaborate nonlinear constitutive models under investigation.

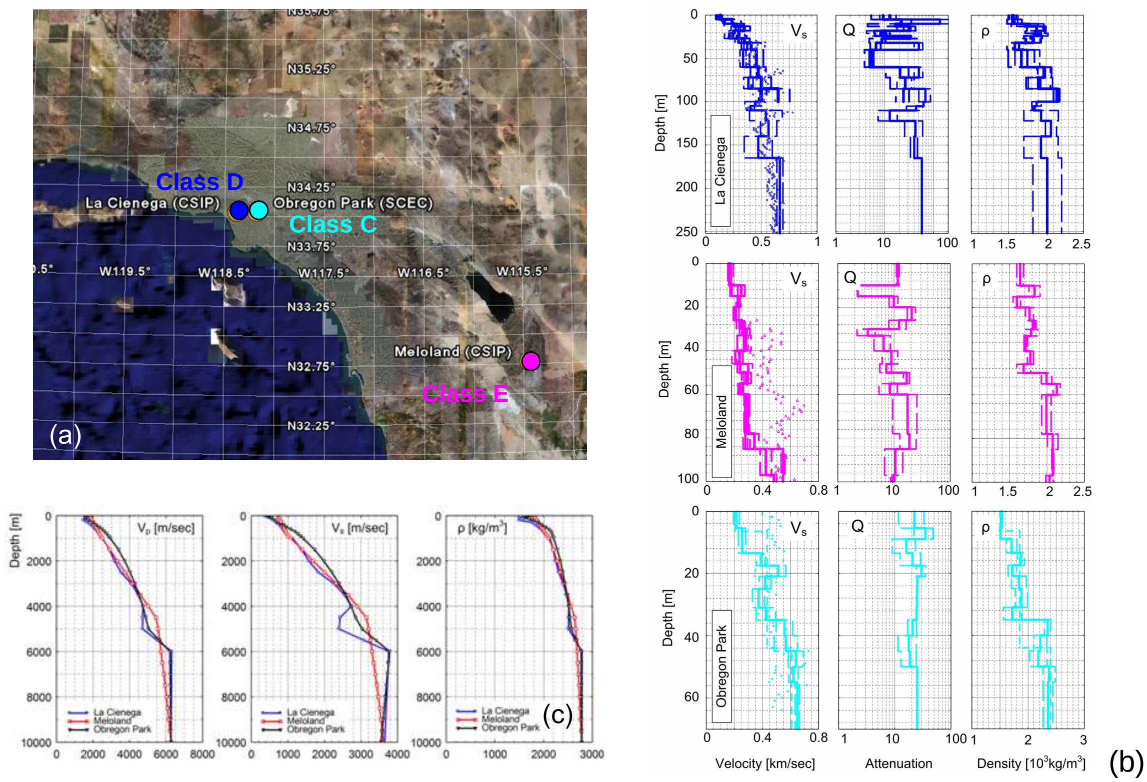

Figure 1 (a) Satellite map of the LA basin; (b) V_s, Q and ρ evaluated by means of downhole array seismogram inversion at the three downhole array stations; and (c) 1D crustal models extracted from the SCEC CVM IV and implemented in the broadband ground motion synthetic simulations.

The site response modelling variability is quantified by means of the coefficient of variation (COV) in soil surface-to-rock spectral amplification factors at the three downhole array sites and the ensemble of ground motion synthetics. In particular, the amplification factor corresponding to the jth site response method at period T_j for a given site and ground motion is defined as:

$$A_j(T_i) = (A_j)_i = SA_j(T_i) / SA_{RO}(T_i) \tag{2.1}$$

where $SA_j(T_i)$ is the spectral acceleration computed on ground surface, and $SA_{RO}(T_i)$ is the spectral acceleration estimated on rock-outcrop ground surface (here, the NEHRP BC boundary with V_{s30}=760m/s). Once all site response analysis methodologies have been implemented, the amplification factor COV at period T_i is defined as:

$$(COV)_i = \sigma(A_j)_i / \mu(A_j)_i \tag{2.2}$$

The overall COV of estimated amplification factors is defined as the mean of COV across the entire response spectral period range T_i = [0.04s ~2.0s], namely:

$$(COV)_i = \mu(COV)_i \quad \textbf{(2.3)}$$

Premise of the nonlinearity susceptibility criteria developed in this work is that nonlinear effects during large earthquakes are both a function of the soil stratification in the near-surface, and a function of the ground motion characteristics: the site conditions describe which layers are susceptible, and the ground motion amplitude and frequency identify whether the seismic waves will "see" the soft layers and whether they "carry" adequate energy at the corresponding wavelengths to impose large strains. Also, large COV among the model predictions imply large incompatibilities in the estimated nonlinear response, and this sensitivity suggests that large strains are imposed on the near-surface materials where incremental nonlinear analyses substantially deviate from empirical methods widely employed in practice such as the equivalent linear method.

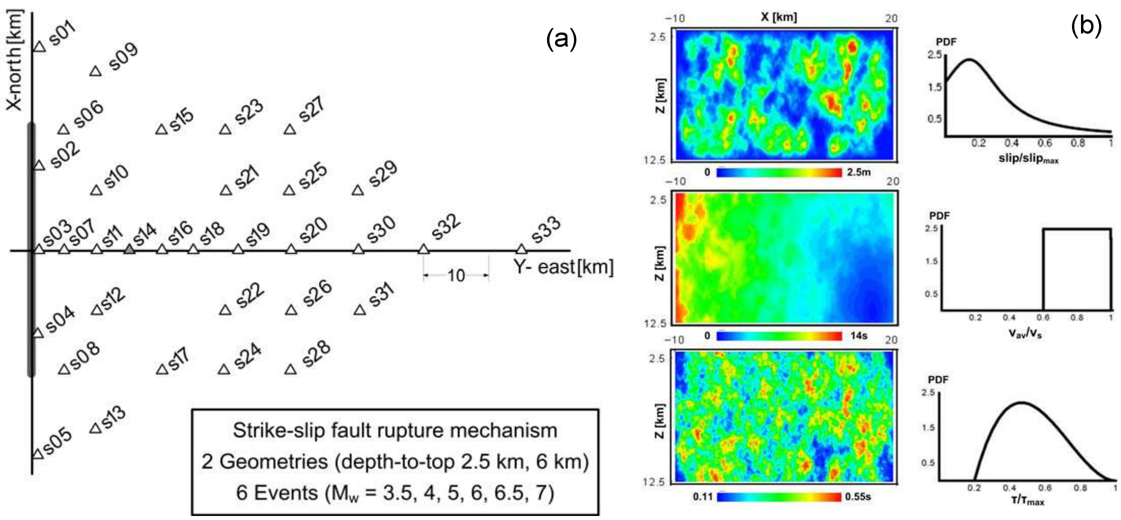

Figure 2 (a) Station layout over a 100×100km^2 grid where broadband ground motion time histories were evaluated for a series of strike-slip rupture scenarios corresponding to 2 fault geometries and 6 magnitudes by means of the hybrid low-frequency/high-frequency approach with correlated source parameters (Liu et al., 2006); and (b) Typical realization of the random distribution of slip, rupture velocity and stress drop over a fault located 2km below the ground surface simulated by means of the Liu et al. (2006) broadband ground motion model.

The ground motion intensity is described by the PGA at rock-outcrop, namely the PGA of the acceleration time history computed prior to the implementation of the nonlinear models. The frequency content of incident seismic motion relative to the amplification potential of the soil profile (transfer function) is described by a frequency index that was developed by Assimaki et al (2008) and corresponds to the normalized cross correlation between the linear elastic transfer function of the profile under investigation and the Fourier amplitude spectrum of the incident motion. More specifically, the frequency index I_f is:

$$I_f = \frac{2\sum_{i=1}^{N}(ATF)_i(FAS)_i}{\sum_{i=1}^{N}(ATF)_i(ATF)_i + \sum_{i=1}^{N}(FAS)_i(FAS)_i} \quad \textbf{(2.4)}$$

where ATF_i and FAS_i are the amplitude of the elastic transfer function of the profile and of the Fourier amplitude spectrum of incident motion, normalized by their respective peak value at the ith frequency point; N is the total number of frequency points in the frequency range of interest, here defined as twice the fundamental frequency of the elastic response for a particular site.

Note that the larger the frequency index, the greater similarity between the transfer function of the profile and the Fourier amplitude spectrum of the incident motion, and therefore the greater amplification potential of a given ground motion at a given site; in case a large I_f value is associated with a high PGA_{RO}, there exists large amplification potential of a strong ground motion, and the anticipated nonlinear effects in the near-surface are also strong. **Figure 3** depicts the variation of the *COV* averaged across the ground surface response spectrum (SA) for the period range T = 0.04 ~ 2.0s as a function of I_f and PGA_{RO}. As can be readily seen, the *COV* in predicted site amplification for the ensemble of strong motion site response methodologies increases with increasing ground motion intensity (PGA_{RO}) and increasing frequency index (I_f), namely attains maximum values at the up-right corner of the contour plot. The PGA_{RO}-I_f regions that correspond to large values of *COV* implying sensitivity of the predicted ground motion to the selected model indicate that incremental nonlinear analyses should be conducted to ensure credibility of the strong motion site response predictions.

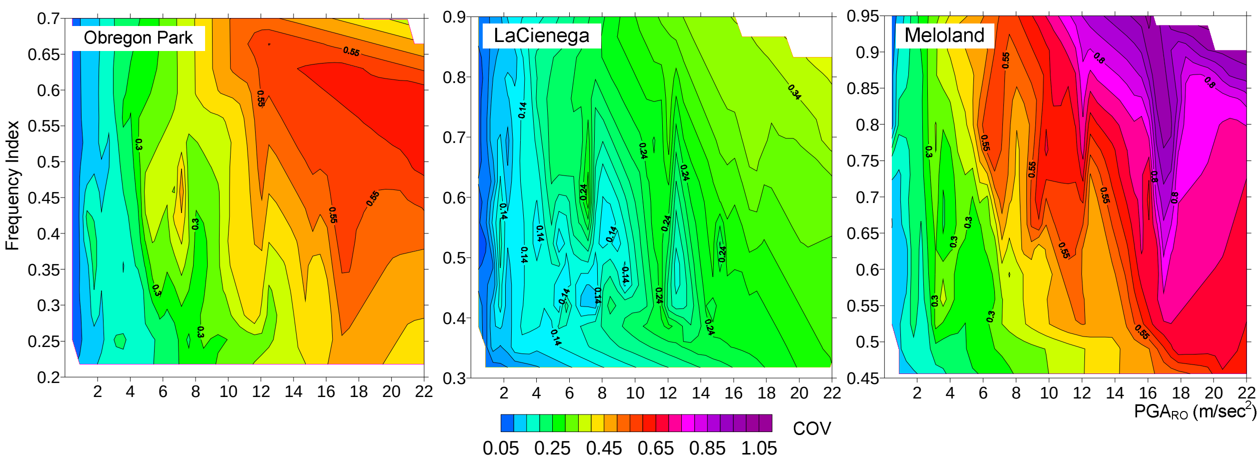

Figure 3 Contour maps of the average coefficient of variation (*COV*) of the predicted site amplification spectrum for the alternative nonlinear models investigated in this study as a function of the peak ground acceleration (PGA_{RO}) on rock-outcrop and frequency index (I_f) for the three sites investigated.

3 STRUCTURAL RESPONSE VARIABILITY AS A RESULT OF SITE RESPONSE MODELING UNCERTAINTY

The proposed frequency index (I_f) was shown to yield very satisfactory results in quantifying the site response modelling variability, indicative of the site nonlinearity susceptibility to a given ground motion. We next investigate the propagation of modelling variability in site response analysis to the assessment of the inelastic structural response of a series of nonlinear SDOF oscillators. In accordance to the previously presented results, we use the proposed criteria to quantify the bias and uncertainty in nonlinear structural response caused by using of different site response methods. In particular, the inelastic deformation ratio (*C*) is used as a measure of nonlinear structural performance, and the variability in *C* resulting from implementation of various site response analysis methodologies is mapped as a function of the developed site- an ground-motion indices, namely as a function of PGA_{RO} and I_f.

3.1 Properties of an inelastic Single-Degree-of-Freedom (SDOF) structure

A monotonic bilinear force-deformation relationship, schematically shown in **Figure 4,** was selected to simulate the idealized inelastic structural response of a series of SDOF's. As shown in **Figure 4**, the elastic stiffness of the model is k and the post-yield stiffness is *ak*, where *a* is the post-yield stiffness ratio. The yield strength is f_y and the corresponding yield deformation of the oscillator is denoted as u_y. Within the linear elastic range, namely u = [0~u_y], the system has a natural vibration period T_n and damping ratio ξ. For such systems it is usefully to define the yield strength reduction factor (R_y) as:

$$R_y = \frac{f_0}{f_y} = \frac{u_0}{u_y} \tag{3.1}$$

where f_0 and u_0 are the minimum yield strength and yield deformation required for the structure to remain elastic during the ground motion, or the peak response values for the corresponding linear system. The peak force is the inelastic system is f_m (**Figure 4**). The peak deformation of the bilinear system is denoted by u_m and the corresponding ductility ratio (μ) is defined as:

$$\mu = \frac{u_m}{u_y} \tag{3.2}$$

Finally, it can be shown that the inelastic deformation ratio (C), which is defined as the ratio of deformations of the inelastic (u_m) over that of the corresponding linear elastic system (u_0), is evaluated as:

$$C = \frac{u_m}{u_0} = \frac{\mu}{R_y} \tag{3.3}$$

Obviously, C is a function of resonant period of structure, and will converge to unity at long periods according to the well-known equal-displacement rule (Veletsos and Newmark, 1960).

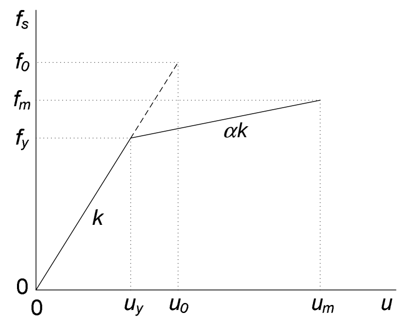

Figure 4 Bilinear force-deformation relationship of inelastic SDOF system and corresponding notation for elastic and post-yield characteristics (after Chopra, 2004)

3.2 Bias and uncertainty in the prediction of the inelastic deformation ratio (C)

We next evaluate the inelastic deformation ratios (C) resulting from implementation of the various site response analysis methodologies, and denote the alternative results by introducing subscripts that correspond to abbreviations of the site response method. For instance, the C value for a given structure on a given, site, whose response to a given ground motion has been evaluated by means of a linear elastic site response analysis will be denoted as $C_{\mathrm{LIE.}}$ Similarly, the C value computed by means of the inelastic constitutive soil model by Kondner and Zelasko (MKZ) model will be denoted as C_{MKZ}. The bias and uncertainty in predictions of C will be represented by the *mean* and the *COV* (coefficient of variation) of q_{C}, defined as the ratio of C of two alternative methods. For example, q_{C} between the LIE and MKZ models is defined as:

$$q_C = \frac{C_{LIE}}{C_{MKZ}} = \frac{u_{m,LIE}}{u_{m,MKZ}} \tag{3.4}$$

Note that deviation of q_c from unity indicates deviation of the predictions in the inelastic structural response due to the use of different site response methodology and thus propagation of the sensitivity of the ground response assessment to the prediction of the structural inelastic performance. **Figure 5** shows the mean of q_{C} for R = 4 at each of the three sites as a function of period; the mean q_{C} is here averaged within the ranges of I_f indicated by the legend of **Figure 5**, and for all ground motions within a PGA_{RO} range of [0.2 ~ 2.0g]. A constant R was here selected to illustrate results of our study, to depict purely the propagation of ground motion modeling variability to the inelastic structural response prediction while keeping the inelastic structural characteristics invariable.

As can be seen in **Figure 5**, all the three sites show highly biased estimation of C by LIE method (i.e show q_{C} < 1.0) in the low-to-medium period range. Results also suggest that the bandwidth of biased results is inversely proportional to the shear wave velocity of the site, i.e. the soil profile stiffness. More specifically, the site corresponding to Class E (Meloland) shows the broadest band of bias, while Obregon Park (Class C) and LaCienega (Class CD) have comparable V_s in the near-surface larger than Meloland (i.e. are stiffer sites), and show comparable bandwidth of bias. This observation may lead to the conjecture that the bias in estimation of C from LIE method relative to incremental nonlinear analyses (here implemented by means of the MKZ soil model) is due to the fact that since the LIE analysis may not reproduce nonlinear soil effects, for a given ground motion, softer sites will amplify motions with longer period content, thus causing broader band of bias in *C* estimation. One more indication supporting the above conjecture is the absolute bias in *C* estimation. The highest and comparable biases ($q_C \approx 0.2$) in Obregon Park site and Meloland site are consistent with the fact that these two sites showed comparable intensity of nonlinear response COV larger than La Cienega. An additional evidence for the conjecture is by evaluating the averaging of q_C across multiple frequency index (I_f) bands. For all the three sites and in the region of highest bias, an increasing trend of bias with increased frequency can be observed. Since the frequency index is an indication of the intensity of nonlinear effects at the site, the correlation between computed structural response bias and site response frequency index (I_f) is supporting of the above conjecture.

Finally, it should be noted that the bias trends in **Figure 5** are consistent with results published by Bazzurro et al. (2004), which were based on the comparison between the inelastic structural response between synthetic and recorded ground motions. This consistency implies that bias in the latter study may be caused by insufficient consideration of nonlinear site effect in the synthetic ground motion predictions.

Next, **Figure 6** shows the COV (coefficient of variation) for the same q_C values within the same I_f ranges as shown in **Figure 5**. Note that while the period regions of high COV coincide with the regions of high bias, the COV for different q_C groups are on the same order of magnitude, a consistency that indicates that the bias estimations in **Figure 5** are not biased. Finally, **Figure 7** shows contour maps of q_C for a constant yield acceleration of 0.2g as a function of the peak ground acceleration (PGA_{RO}) and the frequency index (I_f) for the three sites at four periods. As expected, no trend in PGA_{RO}-I_f dependency is observed in this case: for structures of a constant yield force (f_y), the highly variable intensity of ground motion in the ensemble of synthetics results in highly variable values of R. As a result, the inelastic structural response plotted in **Figure 7** primarily reflects the variability in R, while the impact of the selected ground response methodology is overshadowed. Contour maps of q_C for a larger constant yield acceleration of 1.0g also showed similar results, implying that the response variability is primarily dominated by the highly variable *R* minimizing the effects of nonlinear site response.

4 CONCLUSIONS

We investigated the site response modelling uncertainty in "rupture-to-rafters" ground motion simulations at three sites in Southern California by combining downhole observations and broadband ground motion synthetics. The variability in ground response predictions caused by the selection of site response model was presented in an intensity-frequency (PGA_{RO}-I_f) domain and a consistent ground response variability pattern was observed, namely high intensity-high frequency index regions indicated independent of the soil profile characteristics that nonlinear analyses should be employed for the realistic estimation of site effects. The propagation of site response modelling uncertainty to the assessment of inelastic structural response for bilinear SDOF's revealed consistent bias and uncertainty in the response as a result of the input ground motions predicted by means of the alterative nonlinear site site response models.

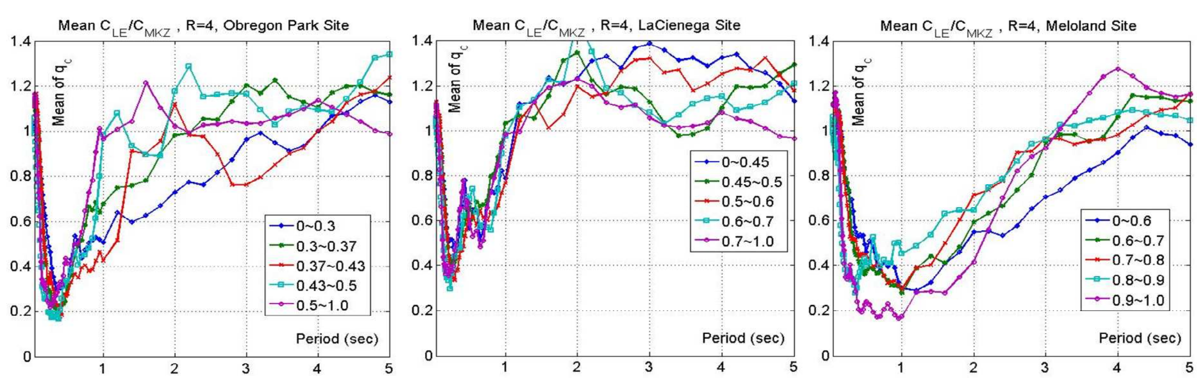

Figure 5 Mean of q_C averaged across five frequency index regions for structures with constant R=4 at the three sites investigated and within a PGA_{RO} range of [0.2 ~ 2.0 *g*]

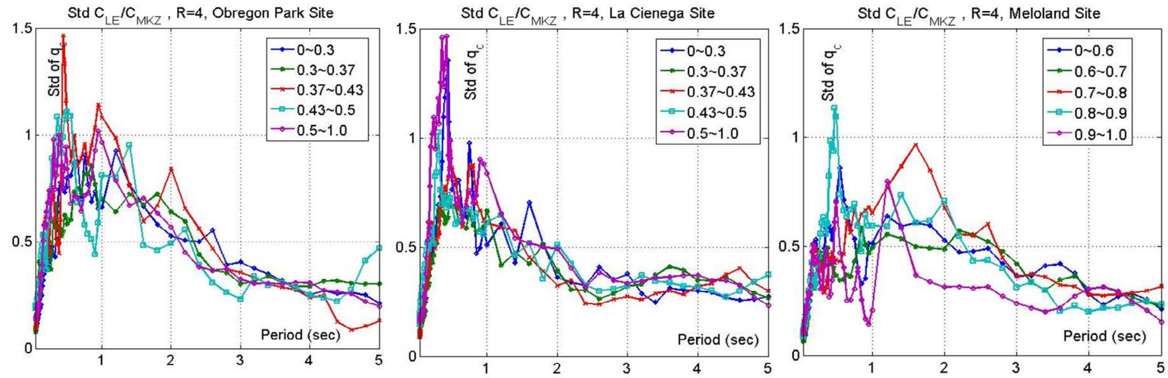

Figure 6 COV of q_C averaged across five frequency index regions for structures with constant R=4 at the three sites investigated and within a PGA_{RO} range of [0.2 ~ 2.0 g]

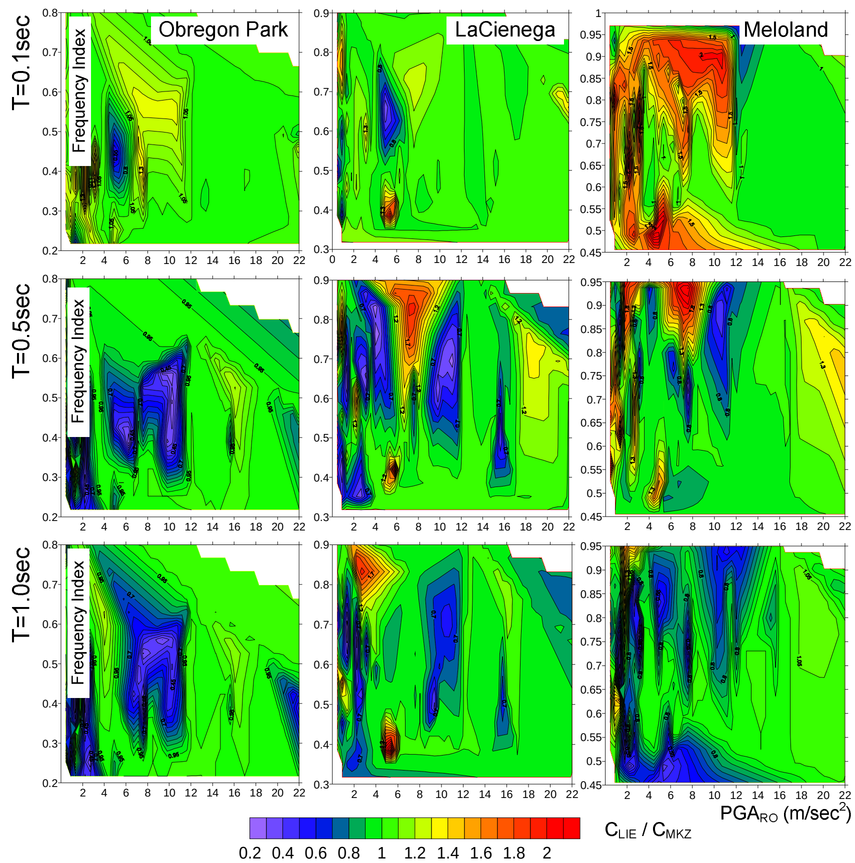

Figure 7 Contour maps of q_C for constant yield acceleration of 0.2g as a function of the peak ground acceleration (PGA_{RO}) at rock-outcrop and the frequency index (I_f) for three sites investigated at T=0.1, 0.5, 1s

Results indicate that the insufficient incorporation of nonlinear site effects in ground motion models could be a possible reason for the bias that has been observed in predictions of inelastic structural response evaluated by means of real recordings vs. synthetic ground motions. To that end, the proposed frequency index could be used to quantify bias in structural response resulting from uncertainties in ground motion predictions. Results from the limited number of sites investigated suggest that the intensity-frequency criteria consistently reflect uncertainties in ground motion predictions attributed to nonlinear effects from rupture-to-rafters, and could therefore lead to the development of guidelines for the efficient integration of site response analyses in large-scale seismological models intended for implementation in PBD procedures. Undoubtedly though, a statistically-significant number of site conditions and ground motion scenaria need to be evaluated for the target guidelines to be developed and implemented in engineering design practice and seismology.

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