Validation of hazard-compatible stochastic ground motion model modification techniques

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ABSTRACT: An important consideration for the adoption of stochastic ground motion models in performance-based earthquake engineering applications is that the probability distribution of target intensity measures from the developed suites of time-histories is compatible with the prescribed hazard at the site and structure of interest. The authors have recently developed a computationally efficient framework to modify existing stochastic ground motion models to facilitate such a compatibility. For a given seismicity scenario, the framework identifies the modified stochastic ground motion model that can sufficiently match the prescribed hazard while maintaining similarity to regional physical ground motion model characteristics. This paper extends this effort through a validation study. Suites of recorded and stochastic ground motions, whose spectral acceleration statistics match the mean and variance of target spectra within a period range of interest, are utilized as input to perform response history analysis of inelastic single-degree-of-freedom case-study systems. The resultant engineering demand parameters distributions are then compared to assess the effect of the proposed modification.

1. INTRODUCTION

Performance-based earthquake engineering (PBEE) uses response history analysis (RHA) as a tool to quantify the expected seismic performance of a structure. Such analysis requires as input ground motion acceleration time-histories that are consistent with the seismic hazard at a given site for each examined structure. Selection and scaling of recorded ground motions based on target intensity measures (IMs) is undoubtedly the most commonly used approach for such a modeling (e.g., Lin et al. 2013), with commonly adopted IM the spectral acceleration at a given period T_i (typically, the fundamental structural period), denoted herein as $S_a(T_i)$. An alternative approach for ground motion modelling that has been receiving increasing interest during the past decade is the use of simulated ground motions derived by stochastic ground motion models (e.g., Rezaeian and Der Kiureghian 2010, Vlachos et al 2018). These models are able to produce acceleration time-histories by modulating a white-noise sequence through functions that address spectral and temporal features of the ground shaking. The parameters of the frequency and time domain functions are related to seismicity and site characteristics through predictive relationships. These relationships are the essential component for the use of stochastic ground motion models for PBEE, relating seismicity to excitation.

The established formulations for these predictive relationships do not necessarily guarantee, though, that the ground motion model will provide acceleration time-series that are consistent with desired target IMs (e.g, Rezaeian and Der Kiureghian 2010), something that has raised concerns for their implementation in PBEE settings. To address this concern the authors recently (Tsioulou et al. 2018a; Tsioulou et al. 2018b) developed a computational efficient framework to modify existing stochastic ground motion models with a dual goal of (a) facilitating compatibility with the target conditional hazard described through any chosen IM while (b) preserving desired trends and correlations in the physical characteristics of the resultant ground acceleration time-series. This paper extends this effort through a validation study by comparing the seismic demand of hazard-compatible recorded ground motions to the demands of stochastic ground motion models that are modified to match the same target hazard.

2. STOCHASTIC GROUND MOTION MODEL MODIFICATION

The stochastic ground motion model considered (and modified) is the one developed by Rezaeian and Der Kiureghian (2010), which combines a time-domain modulating envelope function with a frequency-spectrum with time varying spectral properties. The model parameter vector, denoted as $\boldsymbol{\theta}$ herein, consists of: the parameters of the envelope function, corresponding to the Arias intensity, the significant duration, and the time at the middle of the strong-shaking phase; and the parameters of the frequency-spectrum, corresponding to the damping ratio, the mean spectral frequency and the rate of change for that frequency. These model parameters are related through predictive relationships to seismicity and local site parameters: the moment magnitude, M, the rupture distance, r_{rup}, the fault type, F, and the shear wave velocity in the upper 30 meters of soil, V_{s30}. The vector of these four parameters is denoted as $\mathbf{z}$ herein. The predictive relationships developed by Rezaeian and Der Kiureghian (2010) ultimately define a conditional probability distribution that relates $\boldsymbol{\theta}$ to $\mathbf{z}$, denoted herein as $p(\boldsymbol{\theta}|\boldsymbol{\mu}_r(\mathbf{z}),\boldsymbol{\Sigma}_r)$, where $\boldsymbol{\mu}_r(\mathbf{z})$ are the mean predictions and $\boldsymbol{\Sigma}_r$ represents the variability of these predictions. This ground motion model description ultimately provides a probabilistic prediction for any IM of interest, with variability in the predictions stemming from both (i) the stochastic characteristics of the ground motion model (i.e., fact that it entails a white noise sequence); and (ii) the probabilistic description of the predictive relationship between $\mathbf{z}$ and $\boldsymbol{\theta}$ (i.e., the fact that $\boldsymbol{\Sigma}_r$ exists). For spectral acceleration at a given period T_i, which is the IM utilized in this paper, the probabilistic description through the ground motion model is denoted as $p_g(\ln(S_a(T_i))|\boldsymbol{\mu}_r(\mathbf{z}),\boldsymbol{\Sigma}_r)$ and, as shown in (Tsioulou, et al. 2018a), can be approximated very well as a lognormal distribution utilizing simply the median and dispersion [under the aforementioned two sources of variability (i-ii)] of $S_a(T_i)$. A complete mathematical description of all these statistics is available in (Tsioulou, et al. 2018b).

The modification framework developed by the authors (Tsioulou, et al. 2018b) adjusts $\boldsymbol{\mu}_r(\mathbf{z})$ and $\boldsymbol{\Sigma}_r$ (replaces them with $\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$, respectively) for each examined $\mathbf{z}$ so that the conditional (to the seismicity scenario defined by $\mathbf{z}$) seismic hazard established through the modified model, $p_g(\ln(S_a(T_i))|\boldsymbol{\mu},\boldsymbol{\Sigma})$, provides a closer match to the desired target seismic hazard for the IM, $p_t(\ln(S_a(T_i)|\mathbf{z})$. In the context of this study, the latter is determined through GMPE predictions for the mean and dispersion of $S_a(T_i)$ considering a range of periods T_i. This ultimately facilitates a GMPE-based (or scenario-based) spectra compatibility of the modified stochastic ground motion model. This modification is expressed as a multi-objective optimization problem with two competing objectives. The first objective, F_1, is to minimize the discrepancy of the target seismic hazard to the hazard predicted through the ground motion model, i.e. to a comparison between $p_g(\ln(S_a(T_i))|\boldsymbol{\mu},\boldsymbol{\Sigma})$ and $p_t(\ln(S_a(T_i)|\mathbf{z})$. The second objective, F_2, is to establish the smallest deviation between the updated probability model $p(\boldsymbol{\theta}|\boldsymbol{\mu},\boldsymbol{\Sigma})$ and the initial predictive relationships $p(\boldsymbol{\theta}|\boldsymbol{\mu}_r(\mathbf{z}),\boldsymbol{\Sigma}_r)$, so that consistency with the physical characteristics of the resultant ground motion simulations with the regional trends observed in recorded ground motions is achieved. The relative entropy is utilized to quantify both these objectives, corresponding ultimately to the difference between probability distributions, and a computational framework relying on surrogate modelling (Tsioulou et al. 2018b) is leveraged to efficiently solve the resultant multi-objective optimization. A simplified implementation of this framework also exists (Tsioulou et al. 2018a) that completely ignores variability in the predictive relationships, i.e. enforces $\mathbf{\Sigma}=\mathbf{\Sigma}_r=\mathbf{0}$ (variability stemming from stochastic features of ground motion model still considered), and establishes compatibility with respect to the median IM predictions, rather than the complete hazard (median and dispersion of predictions). This simplified version yields significantly higher computational efficiency (Tsioulou et al. 2018a) with the caveat, of course, that the dispersion of the predictions is not explicitly optimized. Objective F_1 is expressed in this case as the average squared relative error for $S_a(T_i)$ between the ground motion predictions and the GMPE-target across the considered periods, whereas objective F_2 as the weighted squared difference between $\boldsymbol{\mu}$ and $\boldsymbol{\mu}_r(\mathbf{z})$. The simplified implementation is references herein as IMC with the full one referenced as HC.

The solution of this multi-objective optimization problem for either case leads to a Pareto set of dominant solutions expressing a different compromise between the two competing objectives. The representation of the Pareto set in the performance objective [F_1, F_2] space, is termed as the Pareto front. Figure 1 shows representative Pareto fronts for some of the seismicity scenarios discussed later in this paper. The front ranges from the unmodified model, denoted U_n herein, corresponding to F_2=0 and higher discrepancy from the IM-target (larger F_1 values), to models that establish high compatibility to the IM-target (small F_1 values) at the expense of significant deviation of the model characteristics from the initial predictive relationships (large F_2 values). One can eventually select a model configuration from the identified Pareto set that yields the desired hazard compatibility (or strictly IM compatibility for IMC) based on objective F_1 without deviating significantly from regional ground motion characteristics based on objective F_2.

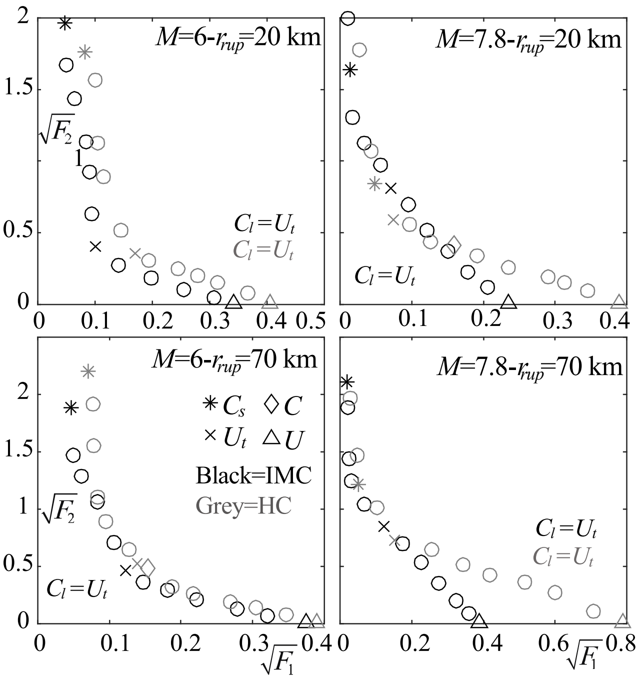

Figure 1: Pareto fronts for the stochastic ground motion modification for indicative seismicity scenarios for IMC (black) and HC (gray).

Following recommendations in (Tsioulou et al. 2018a; Tsioulou et al. 2018b), three specific points are examined, also shown in Figure 1. The first one, denoted U_t, is the point with minimum distance from the Utopia point, corresponding to the minimum of the two objectives across the Pareto front. U_t offers a balanced compromise between the competing objectives and, as shown also in Figure 1, improvement of one objective is typically established away from that point with greater sacrifices in the other objective (front has steep slope). The other two chosen points are defined as the ones that achieve a predetermined compatibility with respect to target hazard, i.e. a specific threshold value of objective F_1. The first of these points, denoted C_s, corresponds to high compatibility (small F_1 threshold), whereas the second point, denoted C_l, is defined following the multi-level criterion proposed by Tsioulou et al. (2018a, 2018b): select the point that provides a moderate compatibility (larger threshold for F_1 compared to C_s) unless that point provides a smaller compatibility to the target than U_t; for those instances update C_l=U_t. This update avoids defining a C_l point that belongs to the steep part of the Pareto front with respect to objective F_2, and is explicitly denoted herein though use of C_l=U_t symbolic terminology. The thresholds for $\sqrt{F_1}$ defining C_s and C_l points are taken as 0.014 and 0.05 for the IMC and HC cases, respectively, for C_s and 0.07 and 0.15 for the IMC and HC cases, respectively, for C_l. These thresholds are chosen here to represent high and moderate compatibility for C_l and C_s respectively.

3. VALIDATION STUDY DETAILS

Following similar studies (Galasso et al. 2012), validation is performed for specific seismicity scenarios corresponding to combination of M = [6, 6.9, 7.8] and r_{rup} = [20, 70] km for a strike-slip fault, with shear wave $V_{s,30}$ = 600 m/s. Note that these are the four characteristics needed to define the stochastic ground motion model input (vector **z**). For the remainder of this paper seismicity scenarios with M=[6, 6.9, 7.8] and r_{rup}=20km are referred to as Scenarios 1, 2 and 3, respectively, and scenarios with M=[6, 6.9, 7.8] and r_{rup} = 70km as Scenarios 4, 5 and 6, respectively. As target IMs, $S_a(T_i)$ in the period range 0.2T_1-1.5T_1 are utilized, where T_1 is the fundamental period of the structure. An elastic period of T_1=1 s is selected, which is typically used as representative fundamental period of mid-rise buildings. The median and dispersion for the target IMs are given for each T_i as the average of four GMPEs used in the Western US, namely the ones by Campbell and Bozorgnia, Abrahamson and Silva, Boore and Atkinson, and Chiou and Youngs (Power et al. 2008). For each of the seismicity scenarios the stochastic ground motion model modification is implemented as outlined in the previous section, resulting in the Pareto fronts presented in Figure 1. For the U_n, U_t, C_s and C_l models, 200 synthetic acceleration time-histories are then obtained for the IMC and HC cases to be used as input for RHA.

The ground motion record set that are utilized as reference in the study, denoted as *SR* herein, are selected using REXEL (Iervolino, et al. 2010), a software that is freely available at http://www.reluis.it/ and allows users to select records which on average match a code-based or user-defined elastic spectrum in a desired period range and with specified upper and lower bound tolerances. REXEL is able to identify ground motions with desired seismicity and site characteristics, which is the reason preferred for this study. For each of the examined seismicities, a reference set of 30 ground motion records was selected from the SIMBAD databases (Smerzini, et al. 2014) matching the median GMPE predictions discussed in the previous section in period range 0.2T_1-1.5T_1 with a deviation from the target of ± 20%. A uniform scaling was applied to all the records so that they match exactly the IM target for the fundamental period T_1=1 s. This was done so that for the elastic SDoF response examined later the reference case is identical to the set target, since *SR* is taken as the benchmark reference for the RHA.

4. SDOF MODEL CHARACTERISTICS

The validation study is performed for an of inelastic SDoF systems with peak-oriented hysteretic behavior and strain hardening with post-yield stiffness corresponding to 10% of the initial stiffness. The initial (elastic) SDoF stiffness is determined based on the fundamental period T_1 of 1 s whereas a constant mass-proportional viscous damping coefficient corresponding to a 5% critical damping ratio (based on elastic stiffness characteristics) is used. The yield strength, F_y, is chosen based on the elastic demand of the SDoF system through strength reduction factor R, defined as the ratio of elastic base shear demand (peak elastic restoring force) to F_y. Different values of R are considered. The linear behavior (F_y=∞) is also considered in this study and, for unification of presentation, it will be frequently referenced as R=1. For determining the elastic base shear demand, and therefore the values for R and F_y, the same value of R is assumed for each record examined. This means that the yielding strength of the structure F_y varies, ultimately, from record to record. Two different engineering demand parameters (EDPs) are considered: peak inelastic displacement, Δ_{in}, and the hysteretic energy, E_H, given by the restoring force work.

5. COMPARISON TO TARGET SPECTRA

Figure 2 shows the average elastic spectral estimates from the suite of recorded *SR* and stochastic ground motions corresponding to models U_n, U_t, C_s and C_l for the IMC case. The target spectra are also shown. For *SR*, statistics are shown for the motions obtained directly from REXEL, without the scaling. Plots for the HC case are very similar and not shown due to space limitations. Figure 3 presents the dispersion of the spectral estimates.

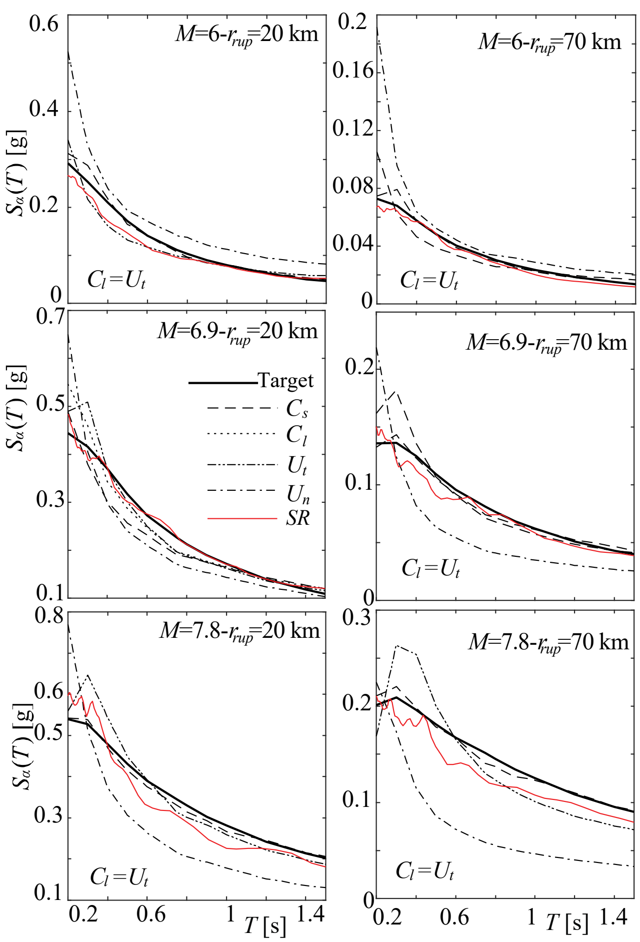

Figure 2: Spectral plot comparison of target spectra and average predictions of recorded (SR) and stochastic ground motions for IMC.

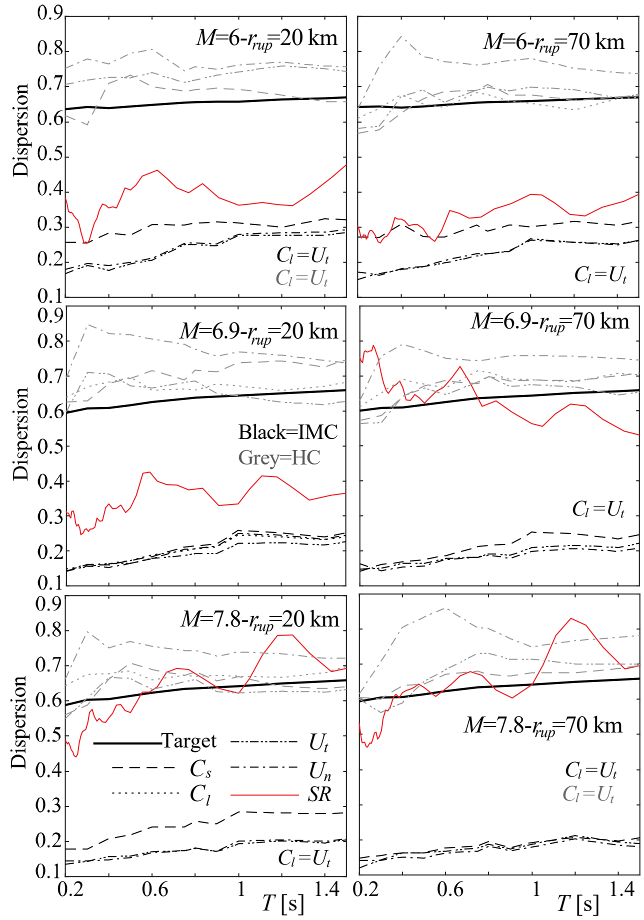

Figure 3: Spectral plot comparison of target dispersion and dispersion for recorded (SR) and stochastic ground motions for IMC and HC.

The recorded *SR* ground motions have high compatibility with the target while trends for the stochastic ground motion suites agree with the ones presented earlier in Figure 1 with respect to the discrepancy from the target (F_1 values). The unmodified model, U_n, does not provide a good match to the desired target for some seismicity Scenarios, overpredicting the resultant spectral acceleration values for small *M* values and underpredicting them for large *M* values. The proposed modification (U_t, C_s and C_l models), facilitates in all instances an improved match, further validating the ability of the modification framework proposed by Tsioulou et al. (2018a, 2018b) in facilitating an improved match to a target IM.

With respect to the dispersion (Figure 3), all IMC models significantly underestimate the target variability. This leads to smaller response dispersion compared to the one observed in the recorded ground motions, and corresponds to an important shortcoming of the IMC modification approach when that dispersion is also of importance (e.g., when assessing collapse risk due to more extreme ground motion records). The HC case, on the other hand, can explicitly control this dispersion, and as evident from Figure 3, high compatibility is achieved for the modified models U_t, C_s and C_l improving upon the unmodified one U_n. Finally, the dispersion of the recorded ground motions (*SR*) is higher than that of IMC modifications and, for some scenarios, reaches or exceeds the target.

6. COMPARISON OF INELASTIC DEMAND

Focus is shifted next to the validation study in terms of structural response. For each seismicity scenario, the suites of recorded and simulated ground motions are used as input to the different SDoF systems to perform nonlinear RHA. For each considered system and EDP, Δ_{in} and E_H, the median and dispersion statistics are estimated across each suite. For the synthetic ground motions, results are reported for the IMC and HC cases together in each figure using color pattern black and gray, respectively. To more clearly depict differences with respect to the reference (benchmark) *SR* results, the relative error *E*(.) between the response output for any stochastic ground motion modification case and *SR* is used.

Figure 4 presents the relative error $E(\bar{\Delta}_{in})$ for the median Δ_{in} estimates, $\bar{\Delta}_{in}$. Figure 5 presents results for the relative error $E(\bar{E}_H)$ for the median hysteretic energy burned E_H, $\bar{E}_H$. Results show that the proposed modification facilitates overall a better match to the reference results of the recorded ground motions in terms of median response statistics. Exceptions to this general trend exist only for significant degree of inelastic behavior (*R* value equal to 8) and for scenarios for which the unmodified model provided a good match to the (elastic) target hazard to start with (Scenarios 2 and 5). In those instances, the unmodified ground motion model has a better match to the *SR* statistics. Note, though, that the error of the proposed modification in these instances is still small. This is not true for the unmodified model which has errors exceeding 100% in some instances. The modification also contributes to smaller sensitivity of the behavior across the different examined scenarios; even though great variability is observed for the unmodified model U_n across the different scenarios, this variability is reduced for the results of the modified ground motion models. This variability is small for *R*=1 as expected (since modification matches the target for elastic behavior) and increases as degree of inelastic behavior increases (larger values of *R*). For small values of *R*, there is a strong correlation of the results to the *R*=1 case for Δ_{in} and therefore to the results reported in Figure 2 or the reported F_1 values in Figure 1.

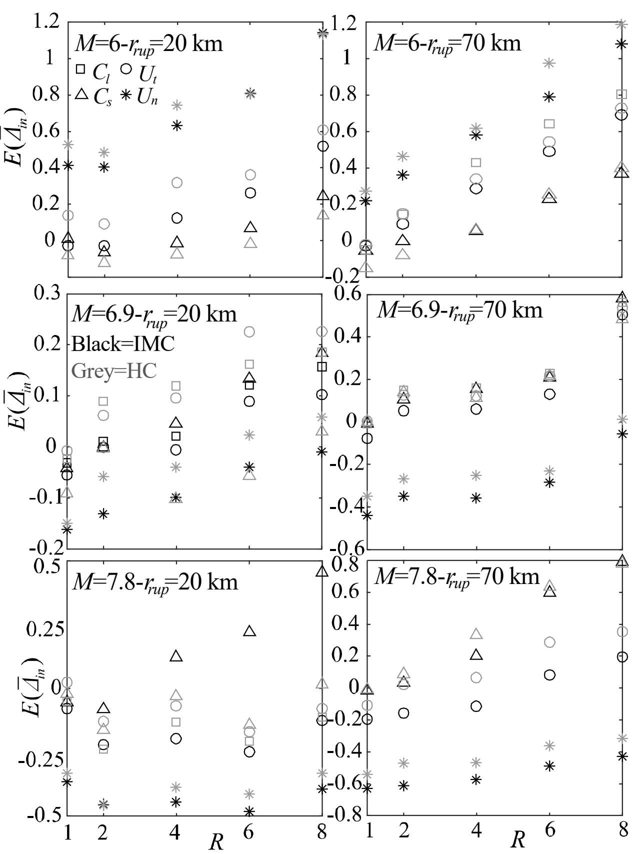

Figure 4: Relative error compared to reference SR response for the peak inelastic displacements

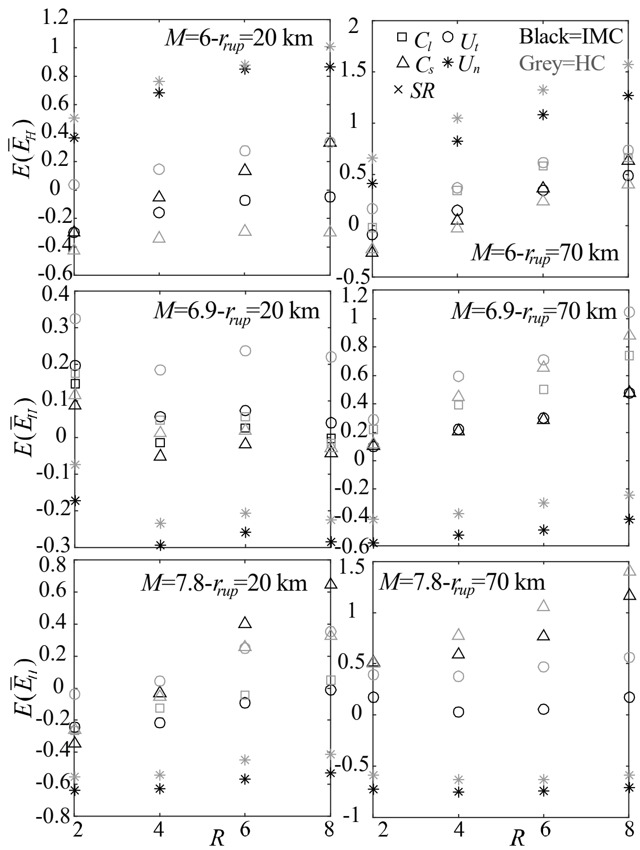

Figure 5: Relative error compared to reference SR response for the hysteretic energy

Note that for large values of R, the nonlinear structural response is sensitive to spectral ordinates at periods much larger than the fundamental one (e.g., due to period elongation stemming from the strong nonlinear behavior); the chosen period range for spectral compatibility (i.e., $0.2T_1$-$1.5T_1$) may not be conservative in those cases (Katsanos and Sextos 2015), yielding the observed large variability for larger values of R.

In general, the IMC and HC modification cases yield very similar trends for the median response and similar results apart from some large R value instances for Scenario 3. Comparing the different modification implementations, C_s provides overall the smallest errors apart from large values of R for Scenarios 3 and 6. This might lead someone to conclude that the significant alteration of ground motion physical characteristics, established in the C_s case, might have an impact when looking at high levels of inelastic behavior. Still even for these two scenarios the recommended modification, corresponding to C_l (which recall is equal to U_t in some instances), yields small errors. All these trends hold for both the peak displacement as well as for the hysteretic energy.

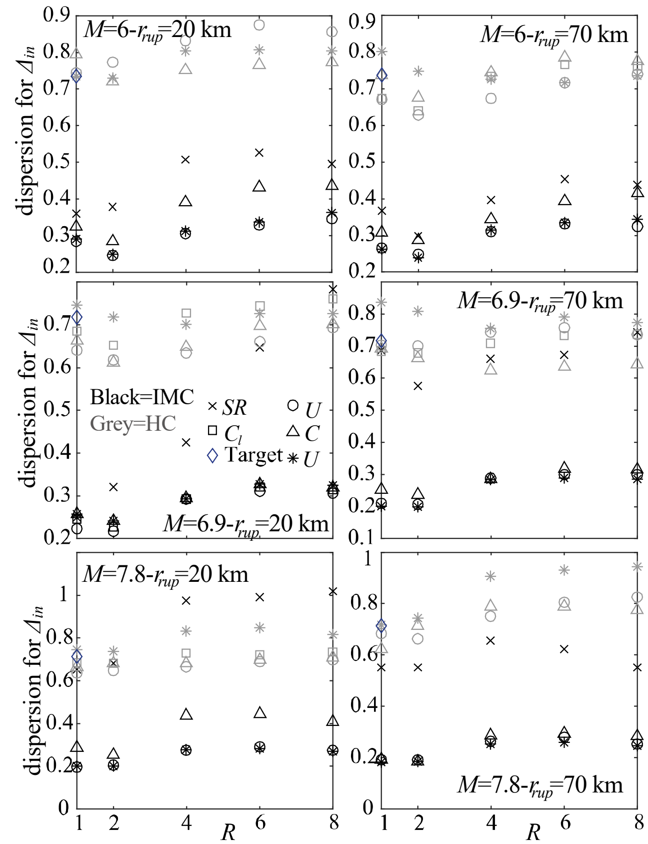

Figure 6: Dispersion (expressed through coefficient of variation) of peak inelastic displacement

Figure 6 presents dispersion for Δ_{in}. Results show that the variability trends reported in Figure 3 extend to the inelastic behavior. Significant differences exist for this statistic between the IMC and HC applications, as expected, with HC providing enhanced compatibility to the target or reference/benchmark values. This, once more, demonstrates the importance of facilitating hazard compatibility, rather simply IM compatibility. In general results for most modification implementations are very similar. This should be attributed to the fact that the unmodified model is close to the target dispersion (so small modifications are only required). Variation of *R* in general does not significantly affect the observed dispersion patterns. For the seismicity scenarios for which the spectral dispersion from records (*SR*) is close to the target, the former is also close to the HC modification. For other scenarios the differences between *SR* and the HC modifications remain similar to the differences between *SR* and the target dispersion, apart from Scenario 2 for which *SR* itself demonstrates a bit of irregular trend, with significant variation of dispersion across different *R* values.

7. CONCLUSIONS

A validation study for the stochastic ground motion model modification proposed recently by the authors was performed in this paper. Results show that the proposed modification improves significantly the match to the reference results corresponding to the recorded ground motion model. As the degree of inelastic behavior increases, that is for larger value or *R*, the differences to the reference results increases. Also, for large degrees of modification, larger errors may exist for such instances of significant inelastic behavior. The moderate modification approach proposed in (Tsioulou, et al. 2018a, Tsioulou, et al. 2018b) appears to consistently yield good results across all seismicity scenarios and types of inelastic behavior. Trends were similar for both considered EDPs. With respect to the two types of modifications examined, IM compatibility (IMC) and hazard compatibility (HC), while both match the median statistics similarly well, HC was shown to provide an enhanced match to the target dispersion, with IMC constrained to small dispersion values. It is worth noting that the intent of this study was not to provide a definite judgment about the specific stochastic ground motion simulation method, but rather to illustrate and validate the proposed modification and discuss possible outcomes.

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