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Variability in Drift Demand with Different Earthquake Ground Motion Selection Criteria

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ABSTRACT

ASCE 7 provisions for selecting and scaling earthquake ground motions for nonlinear analyses endeavor to characterize seismic demand and quantify structural response with a small number of records. When selecting and scaling records, the analyst has choices on the selection criteria. An analytical study was undertaken to quantify the impact of the choice of target spectra, conditioning periods, inclusion of pulse motions, and limits on earthquake intensity measures (IMs) on the interstory drift ratio (IDR) demand for an 8-story reinforced concrete shear wall building. The results indicate that larger median IDR values are expected for sets selected with target Uniform Hazard Spectra (UHS) than for those that use Conditional Mean Spectra (CMS) and Conditional Spectra (CS), presumably demonstrating the conservatism associated with using a target UHS. The results suggest that it may be important to consider the magnitude and variability of important IMs, other than spectral acceleration, for reliable quantification of IDR and other structural response parameters.

Introduction

Recent updates to the American Society of Civil Engineers (ASCE) *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7) [1] provisions for selecting and scaling earthquake ground motion records have changed the way in which earthquake demands are accounted for in nonlinear seismic performance evaluations. For example, in ASCE 7-16 [2], the Conditional Mean Spectrum (CMS) was introduced as an alternative to the Uniform Hazard Spectrum (UHS) as the target to which ground motions are scaled. In developing ground motion sets, the analyst is faced with choices that could affect the demands imposed on the nonlinear models. In addition to the target spectra, some of these choices include the periods on which the CMS are conditioned (T^*), the quantity of pulse motions (for near-fault sites), and lower and upper bounds on earthquake intensity measures other than spectral acceleration (e.g., peak ground velocity, PGV, and Arias intensity, I_A). Considerable work has been conducted to advance practical ground motion selection and scaling criteria [e.g., 3-4]. This paper explores how the target spectrum (UHS, CMS, or CS), conditioning periods, inclusion of pulse motions, and bounds on earthquake intensity measures (IMs) affect

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the interstory drift ratio (IDR) estimated by nonlinear analyses for an example archetype building.

Archetype Building and Nonlinear Model Description

The archetype building is an 8-story reinforced concrete condominium with a rectangular floorplan that is 168 ft (51.2 m) in the x-direction and 63 ft (19.2 m) in the y-direction. The building is classified as Risk Category II and Seismic Design Category D, and is designed for construction in downtown Los Angeles, a site for which ASCE 7 requires near fault motions. The building satisfies the requirements of ASCE 7 and the American Concrete Institute (ACI) *Building Code Requirements for Structural Concrete* (ACI 318-19) [5]. The lateral force-resisting system consists of five reinforced concrete walls in the x-direction and four walls in the y-direction. A 3-dimensional nonlinear model of the building was developed in OpenSees [6]. The fundamental periods of vibration in the two principal building axes are $T_{1,max} = 0.81$ s (x-direction) and $T_{1,min} = 0.78$ s (y-direction). Additional details of the building and OpenSees model are provided in Speicher et al. [7].

Target Spectra

Acceleration spectra (Sa) are shown in Figure 1 for three target spectra scenarios that are considered. The first scenario utilizes the UHS. The second scenario utilizes multiple CMS conditioned on $T^* = 0.3$ s, 0.8 s, and 1.25 s. These T^* values are selected to satisfy ASCE 7 requirements that the combined CMS envelopes exceed 75 % of the UHS over the range of periods shaded in Figure 1 ($0.2T_{1,min}$ to $2T_{1,max}$). The third scenario utilizes the CS, which incorporates the CMS mean (μ) and standard deviation (σ), for the same three T^*.

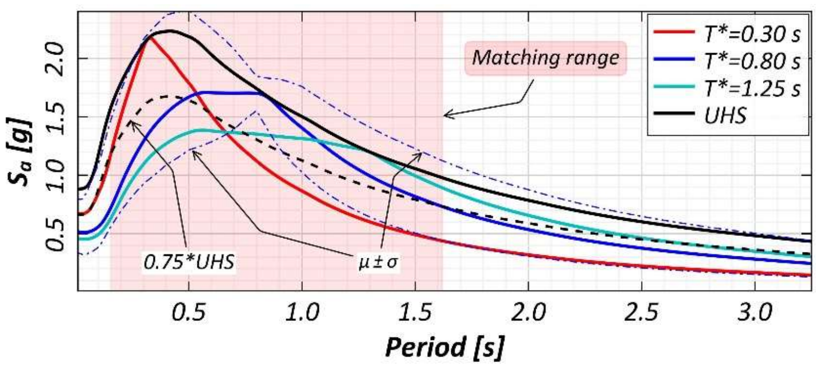

Figure 1. Target UHS, CMS, and CS for site in Los Angeles.

When sets of earthquake records are selected and scaled to target UHS and CMS, which are based on Sa, there is a potential that other important earthquake intensity measures may not be adequately characterized by the set. To investigate other IMs to which the structural response is sensitive, hundreds of earthquake records were scaled to CMS at 7 different hazard levels, with return periods between 72 yr and 10,000 yr, and the records were applied to the OpenSees model. Correlation coefficients (ρ) greater than or equal to 0.89 were calculated between IDR and Sa, I_A, PGV, instantaneous power (IP), and Filtered Incremental Velocity ($FIV3$). IP and $FIV3$ have been shown to be efficient in predicting IDR, especially for when near fault pulses are included in the ground motion set [8,9]. In fact, ρ=0.95 and 0.92 for IP and $FIV3$, respectively, which is similar to Sa (ρ=0.94). In addition to Sa, it may be useful to account for these IMs when selecting and scaling ground motions for this archetype building, which is discussed in more detail in the following section.

Impact of Ground Motion Selection and Scaling Criteria on Structural Response

Several sets of ground motion records were selected and scaled to the target UHS, CMS, and CS shown in Figure 1. Variations of each set were generated to investigate the impact on IDR of different selection criteria, specifically the: (a) quantity of records (n_{GMR}) in the set; (b) minimum quantity of pulse motions in the set ($n_{p,min}$); and (c) bounds on the IM scalar values, denoted as the absolute value of the maximum permissible ε_{IM} (i.e., $|\varepsilon_{max}|$), where $\varepsilon_{IM} = (IM_{val} - \mu_{IM})/\sigma_{IM}$, IM_{val} is the IM scalar value, and μ_{IM} and σ_{IM} are the mean and standard deviation for the IM determined from ground motion models. Thus, for a set with $|\varepsilon_{max}|$=3, the records are selected such that none of their Sa, I_A, PGV, IP, and $FIV3$ values are more than three standard deviations from the mean value (i.e., $\mu_{IM} \mp 3\sigma_{IM}$).

Figure 2 shows boxplots of IDR results for the different ground motion sets. Each set is given a unique numerical identifier (e.g., C4a) that indicates the target spectrum (U=UHS, M=CMS, C=CS). Each of the C and M sets has 3 subsets (a, b, and c) that are comprised of unique records selected based on the same selection criteria. For example, from a selection and scaling standpoint, subsets C4a, C4b, and C4c are acceptable alternatives to one another with completely different records. For each boxplot, the red line is the median (IDR_{50}); the lower and upper extents of the blue box are the 25th and 75th percentile values; the lower and upper black lines indicate the minimum (IDR_{min}) and maximum (IDR_{max}) values that are not considered statistical outliers; and the black crosses are statistical outliers. For the C and M sets, the gray boxplots show the separate results for $T^* = 0.3$ s (leftmost gray boxplot), 0.8 s (middle gray boxplot), and 1.25 s (rightmost gray boxplot). The blue boxplot is for the controlling T^* that produces the largest IDR_{50}, which is generally $T^* = 1.2$ s except for sets C7c and M9a, which are controlled by $T^* = 0.8$ s. IDR_{50} and IDR_{max} values for the UHS target spectra (U1 through U3) are generally around 20 % higher than those for the CMS and CS spectra, which supports the use of multiple conditional spectra to avoid the potential conservatism associated with using a target UHS.

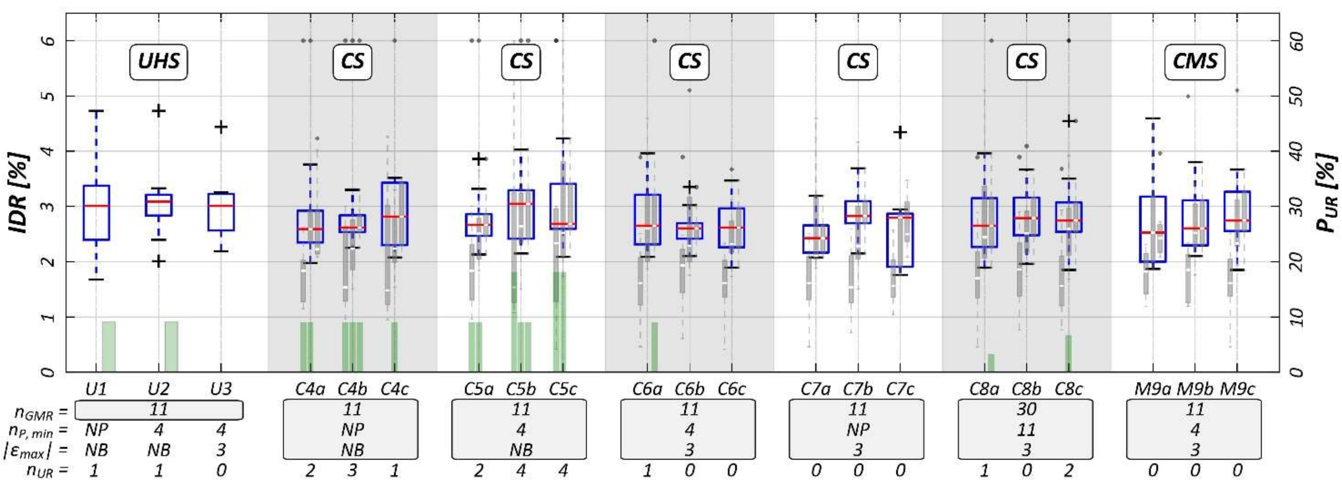

Figure 2. Boxplots of IDR for ground motion sets with different target spectra, IM bounds, and pulse record requirements (Note: NP = no pulse records and NB = no bounds on IMs)

The green bars in Figure 2 indicate the percentage of records with an unacceptable response (P_{UR}), defined herein as any case in which the OpenSees model predicts $IDR_{max} \geq 6$ % (i.e., ASCE 7 Chapter 16 criteria for a single unacceptable response) or more than 20 % lateral strength loss. P_{UR} is calculated as the ratio of unacceptable responses (n_{UR}) to n_{GMR}. It is noted that ASCE 7 permits n_{UR}=1 for a set size of n_{GMR}=11 (i.e., $P_{UR} \leq 9$ %). For sets C5b and C5c, at least one T^* produces n_{UR}=2 (i.e., P_{UR} = 18 %), which would not satisfy the ASCE 7 criteria. However, by bounding the IMs to $|\varepsilon_{max}|$=3 in sets C6, the unacceptable responses are nearly eliminated with n_{UR}=1 for C6a and n_{UR}=0 for C6b and C6c. In Figure 2, it is clear that placing bounds of $|\varepsilon_{max}|$=3 on Sa, I_A, PGV, IP, and $FIV3$ results in lower P_{UR} values. In fact, only 4 of the 398 records selected with $|\varepsilon_{max}|$=3 lead to unacceptable responses (i.e., P_{UR}=1.0 %), whereas n_{UR}=18 for the 220 records with no IM bounds (i.e., P_{UR}=8.2 %). Figure 2 also shows that IDR_{50}, IDR_{max}, and P_{UR} are higher for sets that include pulses, but this appears to only apply to sets selected without IM bounds (i.e., sets C5 and C4). The results suggest that amplitude-scaled records selected without IM bounds have the potential to produce excessively high demands that may not be representative of the seismic scenario, which is discussed in more detail below.

Figures 3a and 3b illustrate the impact of bounding IP, PGV, and $FIV3$ scalar values. Computed ε_{PGV} and ε_{IP} values are shown on the x- and y-axes, respectively, and the computed ε_{FIV} values are indicated by the marker color. The size of the marker indicates the IDR estimated by the OpenSees analyses. The results in Figure 3a include all the sets summarized in Figure 2. Figure 3a shows that all unacceptable results (i.e., $IDR_{max} \geq 6$ %) are for records with one or more of their ε_{PGV}, ε_{IP}, or ε_{FIV3} values greater than 3. Conversely, Figure 3b only includes sets with $|\varepsilon_{max}|$=3, eliminating all but 3 unacceptable results. It is important to point out that all 3 unacceptable responses in Figure 3b are for pulse motions (i.e., triangular marker) with short rupture distances less than 5 km. Note that rupture distance is not indicated in Figure 3.

The results in Figure 3 indicate that placing reasonable bounds on the ground motion IMs leads to records that may be more representative of the seismic scenario, thereby resulting in more reliable characterization of nonlinear structural response parameters such as IDR. Future work should explore ground motion selection and scaling procedures that can better account for the expected distributions of important IMs that affect the nonlinear response of the analytical model.

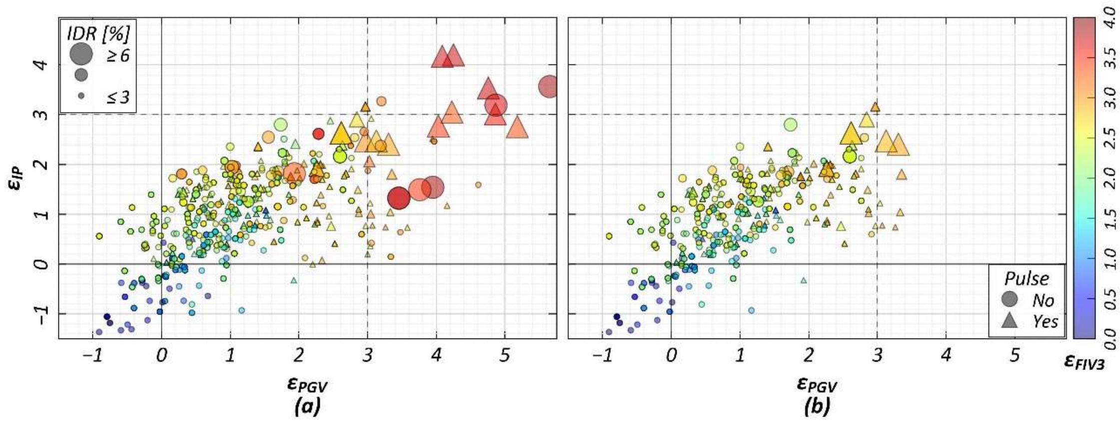

Figure 3. IDR, ε_{PGV}, ε_{IP}, and ε_{FIV3} for (a) all U, C, and M sets; and (b) sets with $|\varepsilon_{max}|$=3

Conclusions and Future Work

The impact of different ground motion selection and scaling criteria on the nonlinear response of an 8-story archetype building was presented. The following conclusions are drawn:

- IDR_{50} and IDR_{max} values for UHS sets are generally higher than those for CMS sets selected under the same criteria, supporting the use of multiple CMS or CS to avoid the potential conservatism associated with using a target UHS.
- When selecting and scaling earthquake ground motion records, reasonable bounds should be placed on the magnitudes on important IMs to ensure the records are representative of the seismic scenario, to achieve reliable quantification of structural response parameters, and to prevent overestimation of unacceptable responses, especially when using few ground motion records (e.g., n_{GMR}=11) and including pulse motions.
- Future work should evaluate how the magnitude and variability of important IMs, treatment of pulse records, and building floorplan and geometry can inform ground motion selection and scaling.

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