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Role of conditioning intensity measure in the influence of ground motion duration on the structural response

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ABSTRACT

Although several research studies have examined some effects of ground motion (GM) duration on the structural responses, many questions in this field remain unexplored and unaddressed. One area that remains a topic of debate in this field is that no outcomes can be found with regard to the effect of GM duration on structural responses when considering different choices of conditioning intensity measures (IMs). This study examines the role of the conditioning IM in the degree that GM duration influences the structural responses. To this end, the seismic demand in three different structural systems from low- to high-rise buildings are estimated using multiple stripe analyses subjected to different sets of GMs from shallow crustal seismic zone. It is found that duration of GMs from shallow events affects the structural response but not as much as that reported for GMs from subductions events. The results also reveal that the importance of GM duration mainly depends on the considered conditioning IM. Specifically, GM duration does not substantially affect the structural responses in terms of probability of collapse if peak ground acceleration, peak ground velocity, spectrum intensity, spectral acceleration at higher modes are implemented as the conditioning IMs. On the other hand, in the case of cumulative absolute velocity and spectral acceleration at the fundamental and lengthened periods, the structural responses are considerably affected by GM duration.

1. Introduction

Ground motion (GM) selection as a tool to develop the seismic input for performing nonlinear dynamic analysis has received considerable attention in recent decades; e.g., [1–10]. Two powerful tools for GM selection were introduced including the conditional mean spectrum [3,6] and its general form called the generalized conditional intensity measure (GCIM) [4,7]. The GCIM approach is able to consider multiple GM parameters or intensity measures (IMs), which may play important roles in predicting the response of a structure. In this approach, the distributions of considered IMs are conditioned on the specific value of a GM parameter in which the seismic hazard for the site is developed—known as the conditioning IM (called IM_j henceforth similar to [4]). Deaggregation plots (e.g., those presented in Fig. 3 in [11]) demonstrate that different seismic sources dominate the seismic hazard of a site at the same annual exceedance probability using different IM_js. Therefore, using different IM_js in GM selection may lead to different ensembles of GMs and consequently different distributions of the structural responses. Several research studies (e.g., [11–13]) have been performed on the appropriate choice of IM_j and its effect on the predicted structural responses. The results of these studies have demonstrated that if an intensity-based assessment is applied, the seismic demand is sensitive to IM_j. When it comes to a risk-based assessment, the choice of IM_j does not have noticeable effects on the structural responses if GMs are selected correctly.

Several studies (e.g., [14–20]) have investigated the importance of GM duration on the response of structural systems. Most of these studies have focused on the degree to which GM duration may influence the structural responses considering: (i) different engineering demand parameters for quantifying the structural responses; (ii) different types of structures; and (iii) the source of earthquake (i.e., longer-duration subduction event or shorter-duration shallow crustal events). For example, Bommer et al. [14] and Hancock and Bommer [15] have shown that GM duration does not have a significant influence on the peak-based damage metrics, while it has a considerable impact on the energy-based damage measures. In addition, several research studies (e.g., [14,17]) have tried to focus on the structural system for evaluating the effect of GM duration. Some recent studies [16–18] focusing on predominantly longer-duration GMs from subduction zones against shorter-duration GMs from shallow events have found that for structures that account for strength and stiffness deterioration as well as the geometric nonlinearity (P-delta effects), GM duration can affect the

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structural collapse capacity. On the other hand, Kiani and Pezeshk [21] have shown that the duration of GMs from shallow events affects the peak-based damage metrics over the rare earthquake intensity levels. Two other important factors that may contribute to the effect of GM duration on the structural responses are the primary IM or the IM_j used to characterize the GM and the metric used for definition of GM duration. Regarding the choice of IM for characterizing GM, most of the mentioned studies have chosen spectral acceleration (*Sa*) at the fundamental period of structure, $Sa(T_1)$, as the IM_j due to its consistency with design provisions. Nevertheless, Bradley [22] and Baker and Bradley [23] have found that significant duration (as a metric for measuring GM duration) is differently correlated with various GM parameters. Therefore, the conditional duration of the expected GMs may differs depending on the applied IM_j. It is still not clear whether the importance of GM duration on the structural responses changes as different IM_j are applied for GM selection. Despite several studies on the effect of GM duration on the response of structural systems, to the best of the authors' knowledge, no study has tried to quantify the sensitivity of the impact of GM duration on the structural responses to the choice of IM_j. In addition, a review of the technical literature reveals that there are not unanimous results about the impact of GM duration on the structural responses given different definitions of GM duration.

Unlike the other studies focusing on subduction events, one objective of this study is investigate the importance of the duration of GMs from shallow crustal seismic zones on the response of building structures. More specifically, the goal of this study is to measure the sensitivity of the structural responses to GM duration considering different IM_js . The next objective of this study is to examine the dependence of the structural responses to different metrics used for quantifying GM duration.

2. Conditional distribution OF GM duration

As stated by Bradley [4,7,11] and many others (e.g., [18,24]) the mean, $\mu_{\ln IM_i|Rup,IM_j}(rup_k,im_j)$, and the standard deviation, $\sigma_{\ln IM_i|Rup,IM_j}(rup_k,im_j)$, of the natural logarithm of an IM, *ln* IM_i, given a specific value of IM_j, $IM_j = im_j$, and a specific earthquake rupture, $Rup = rup_k$, can be computed using the following equations.

$$\mu_{\ln IM_i|Rup,IM_j}(rup_k,\, im_j) = \mu_{\ln IM_i|Rup}(rup_k) + \sigma_{\ln IM_i|Rup(rup_k)}\rho_{\ln IM_i,\ln IM_j}\epsilon_{\ln IM_j} \tag{1}$$

$$\sigma_{\ln IM_i|Rup,IM_j}(rup_k,\, im_j) = \sigma_{\ln IM_i|Rup(rup_k)}\sqrt{1-\rho^2_{\ln IM_i,\ln IM_j}} \tag{2}$$

Where $\mu_{\ln IM_i|Rup}(rup_k)$ and $\sigma_{\ln IM_i|Rup(rup_k)}$ are, respectively, the mean and standard deviation of *ln* IM_i given $Rup = rup_k$ drawn using a GM prediction equation (GMPE). In addition, $\epsilon_{\ln IM_j}$ is the epsilon-value of $\ln IM_j$ and $\rho_{\ln IM_i,\ \ln IM_j}$ is the correlation between the epsilon-values of $\ln IM_i$ and $\ln IM_j$.

Considering that the natural logarithm of IMs follows a log-normal distribution [25–28], the conditional distribution of each IM given $IM_j = im_j$ and $Rup = rup_k$, $f_{IM_i|Rup,IM_j}(im_i|rup_k,im_j)$, can be computed. Then, the conditional distribution of each IM given $IM_j = im_j$, $f_{IM_i|IM_j}(im_i,im_j)$, can be obtained using Eq. (3) considering all earthquake scenarios that affect the seismic hazard of the site [4,7]

$$f_{IM_i|IM_j}(im_i \mid im_j) = \sum_{k=1}^{N_{Rup}} f_{IM_i|Rup,IM_j}(im_i \mid rup_k,\, im_j)P_{Rup|IM_j}(rup_k \mid im_j) \tag{3}$$

Where $P_{Rup|IM_j}(rup_k|im_j)$ is the relative contribution of $Rup = rup_k$ given $IM_j = im_j$ and N_{Rup} is the number of possible earthquake ruptures.

The above equations can be employed to compute the distribution of a GM feature (e.g., duration) conditioned on the occurrence of a specific IM (i.e., IM_j) at a hazard level with a specific probability of exceedance. Remarkably, the computed conditional distribution of an IM significantly depends on the correlation between the epsilon-values of IMs, $\rho_{\ln IM_i,\ln IM_j}$. Table 1 presents the correlation of GM duration in terms of significant duration, $Ds_{5\text{-}75}$ and $Ds_{5\text{-}95}$ [28], and cumulative absolute velocity *CAV* [29] with amplitude- and cumulative-based IMs including: spectrum intensity *SI* [30], peak ground acceleration *PGA*, peak ground velocity *PGV*, *CAV*, acceleration spectrum intensity *ASI* [31], *Sa* at different periods. As seen, the correlations of significant duration with different IMs vary from − 0.44 to 0.70 [22,32]. Therefore, the conditional distribution of duration metrics is not the same for different choice of IM_j. In this regard, Fig. 1 shows the conditional distribution of $Ds_{5\text{-}75}$ conditioned on the values of *PGA* and $Sa(T = 6s)$ for three different hazard levels, which is computed using open-source seismic hazard analysis software, OpenSHA [33]. Results shown in Fig. 1 illustrate that the difference between the conditional distributions of GM duration (here $Ds_{5\text{-}75}$) over different hazard levels is a function of the applied IM_j. In case of $IM_j = Sa(T = 6s)$, the difference between the distributions of $Ds_{5\text{-}75}$ over different levels is not as significant as the one for $IM_j = PGA$. Moreover, Fig. 2 presents the median of $Ds_{5\text{-}75}$ conditioned on different IM_js over a wide range of hazard levels, As seen, the figure demonstrates that at the hazard levels with longer return periods, GMs with longer durations are expected for $IM_j = Sa(T = 6s)$, as compared to when $IM_j = PGA$. The observed difference in the conditional median of $Ds_{5\text{-}75}$ is because of the fact that $Ds_{5\text{-}75}$ is negatively correlated with *PGA* (correlation coefficient of − 0.44), while it has a weak positive correlation with $Sa(T = 6s)$ (correlation coefficient of 0.12). While not the focus of this study, the described difference in the conditional distributions of GM duration given different IM_js is even more pronounced for longer-duration subduction earthquakes. Providing the above illustrations, the following sections examine the role of IM_j on the effect that GM duration may have on the structural seismic demand.

Table 1
Correlations between duration metrics and other IMs [22,32].

IM_j	$Ds_{5\text{-}75}$	$Ds_{5\text{-}95}$	*CAV*
$Sa(T = 0.2\ s)$	− 0.43	− 0.39	0.61
$Sa(T = 0.4\ s)$	− 0.35	− 0.32	0.62
$Sa(T = 0.5\ s)$	− 0.31	− 0.27	0.64
$Sa(T = 0.7\ s)$	− 0.23	− 0.21	0.61
$Sa(T = 0.9\ s)$	− 0.19	− 0.15	0.58
$Sa(T = 1.1\ s)$	− 0.15	− 0.10	0.55
$Sa(T = 1.2\ s)$	− 0.12	− 0.08	0.54
$Sa(T = 2\ s)$	− 0.03	0.04	0.53
$Sa(T = 2.3\ s)$	− 0.01	0.07	0.53
$Sa(T = 3.15\ s)$	0.04	0.14	0.53
$Sa(T = 4\ s)$	0.05	0.14	0.52
$Sa(T = 6\ s)$	0.12	0.17	0.45
PGA	− 0.44	− 0.41	0.70
PGV	− 0.26	− 0.21	0.69
SI	− 0.13	− 0.08	0.68
CAV	0.08	0.12	—
ASI	− 0.41	− 0.37	0.70

3. Considered structural frames and damage measures

In this study the influence of GM duration on the structural responses is investigated by analyzing three special steel moment resisting frame buildings with reduced beam section (RBS) connections with varying frame heights (including 4-, 8-, 16-story buildings). These buildings were previously designed by Jin and El-Tawil [34] for a region in Los Angeles considering a site class with stiff soil. The first three vibration periods for the 4-, 8-, 16-story frame buildings are: (1.1, 0.4, and 0.2), (2.3, 0.9, and 0.5), and (3.15, 1.2, and 0.7) s, respectively. The Open System for Earthquake Engineering Simulations (OpenSees) [35] is implemented for modeling of all three structural systems. As mentioned in Ghassemieh and Kiani [36], an exterior frame is chosen for modeling and analysis. The destabilizing effects of the gravity loads,