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Scenario-Based Ground Motion Selection in the Near-Fault Region

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ABSTRACT

In this paper, the ability of ground motion selection methods to appropriately select records which exhibit pulse-like ground motions in the near-fault region is examined. While the occurrence of forward directivity pulses and their effect on seismic response of engineered systems has been long recognized; and their consideration is advocated in seismic design codes, no commonly accepted procedure exists for ensuring that such records are considered in ground motion selection. Here, particular attention is given to ground motion selection which is explicitly based on ground motion intensity measures (IMs), including pseudo-acceleration response spectrum (SA), duration, and cumulative measures; rather than a focus on implicit parameters (i.e. pulse or non-pulse classifications) that are conventionally used to heuristically distinguish between the near-fault and far-field records. Importantly, it is shown that selection based on an appropriate set of IMs will indirectly lead to a ground motion ensemble with the appropriate proportion of forward directivity motions for a given scenario rupture. Example applications are presented here only for scenario seismic hazard analysis cases with different rupture characteristics, source-to-site geometry, and site conditions. The results indicate that the modification to SA ordinates to account for the directivity pulse effect, and utilizing multiple IMs in the selection process based on the generalized conditional intensity measure (GCIM) approach, results in ground motion ensembles with an accurate representation of the target hazard and the predicted directivity ground motion characteristics.

Introduction

Ground motions in the near-fault region may exhibit characteristics such as velocity pulses and permanent static displacement which are not observed in the far-field ground motions. The occurrence of such characteristics have been long recognized and numerous studies conducted to illustrate the effect of such ground motions on seismic response of engineered systems (e.g., Bertero et al. 1978, Luco and Cornell 2007). Proximity to the seismic source, source-to-site geometry, and specific rupture characteristics can create favorable conditions for the occurrence of ground motions with large velocity pulses. (Somerville et al. 1997, Aagaard et al. 2004). These ground motions, as opposed to pulse-like motions generated by the nonlinear site response or basin generated shear waves, are referred to as forward directivity pulse-like ground motions and are the focus of this study.

Assessing the seismic performance of engineered systems requires an appropriate representation of the seismic hazard at the site. This can be achieved by selecting ground motion time series recorded during past earthquakes that appropriately represent the expected target hazard. Since

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near-fault ground motions with velocity pulses can manifest ground motion intensity measure (IM) values that are notably different than far-field records, neglecting the occurrence of directivity pulses may result in a biased estimation of the seismic response of systems susceptible to such motions. While, various methods have been proposed to select ground motions for seismic response analysis (Baker 2010, Wang 2011, Bradley 2012a), only few recent studies have been concerned with the explicit selection of near-fault ground motions (e.g., Almufti et al. 2013, Hayden et al. 2014), despite the fact that considering near-fault ground motions is advocated in seismic codes – albeit without providing an explicit process to do so (e.g., NZS1170.5 2004, ASCE/SEI7-10 2010).

One of the important issues in the selection of near-fault ground motions is to establish an appropriate 'target' for time series selection (NEHRP 2011). Almufti et al. (2013) recommend using the conditional mean spectrum (CMS) (Baker 2010) including a narrow band modification to account for the directivity pulse effect (Shahi and Baker 2011), while Hayden et al. (2014) also support the CMS as a target with no explicit consideration for the directivity pulse effect. In both methods, the CMS is computed from the governing (or mean) rupture scenario. The use of response spectral ordinates, and not other additional intensity measures, in the above two suggested procedures ignores the fact that ground motion severity is a function of amplitude, frequency content, and duration (Bradley 2010). For example, ground motions with forward directivity pulses frequently have lower significant duration in comparison to the far-field records due to the early arrival of seismic waves energy in a pulse-like motion (Somerville et al. 1997, Hayden et al. 2014)).

The two aforementioned recent approaches for selecting near-fault ground motions also require the separation of the selection process for ground motions with and without directivity pulses (e.g., Almufti et al. 2013, Hayden et al. 2014). While forward directivity is clearly an important phenomenon in the seismic response for some engineering systems, this separation implies that forward directivity is always more important than other factors (which are largely considered in a secondary implicit fashion). Given the fact that a binary categorization of ground motions as: (i) pulse-like, or (ii) non-pulse-like, is to some extent a generic classification of what is a continuous phenomenon (Bray and Rodriguez-Marek 2004, Baker 2007, Hayden et al. 2014, Shahi and Baker 2014), ground motions selected based on this binary categorization may contain directivity pulses that may or may not necessarily have a severe effect on a given engineered system, compared to records without pulses. Given the abovementioned points, a more rigorous approach to select ground motions (for both near-fault and far-field sites) is to perform the ground motion selection based on IMs that explicitly characterize the severity of ground motions (i.e. such IMs are themselves affected by any forward directivity effects).

In this paper, a ground motion selection methodology is illustrated which is able to select ensembles of ground motions for near-fault ruptures without separating the selection process for pulse-like and non-pulse-like records. The selection procedure uses explicit ground motion IMs, including SA ordinates over a wide range of vibration periods, duration, and cumulative IMs, and is based on the generalized conditional intensity measure (GCIM) methodology (Bradley 2010, 2012a), as an extension of the CMS (Baker and Cornell 2006, Baker 2010). It is demonstrated that by considering an appropriate range of IMs, the selected ground motion ensembles contain both an appropriate number of records with forward directivity pulses, and also appropriate pulse period distributions, although neither of these two aspects are explicitly considered in the selection process itself. The reason for this result is the fact that the occurrence and predominant period of velocity pulses do affect the ground motion IMs, and hence are captured in this fashion. In the next section, the different components of the ground motion selection methodology are presented. Subsequently, example applications for scenario seismic hazard analysis cases are demonstrated; and the pertinent implications are discussed.

Considering the Occurrence of Forward Directivity Pulses in Seismic Hazard Analysis

Conventional GMPEs do not explicitly account for the characteristics of near-fault ground motions such as velocity pulses (e.g., Somerville et al. 1997), however, having such records in the databases used for developing GMPEs influences the resulting predictions (Shahi and Baker 2011, Spudich et al. 2014). Attempts have been made to modify the prediction of conventional GMPEs in order to explicitly account for the characteristics of ground motions containing forward directivity pulses by using post hoc modifications (e.g., Somerville et al. 1997, Shahi and Baker 2011, Spudich et al. 2014). A more rigorous approach to address this problem is the direct consideration of the near-fault characteristics in the development of GMPEs (e.g., Chiou and Youngs 2014), which requires improvements in the existing directivity models (Spudich et al. 2014). The method used in this study to account for directivity in the hazard is based on Shahi and Baker (2011), however, instead of separating the hazard calculations for pulse-like and non-pulse-like ground motions, the ‘total’ SA distribution is assumed to be lognormal with the mean and standard deviation accounting for pulse-like ground motions. This approach results in a single target hazard at the site for ground motion selection (refer to Tarbali and Bradley (2015a) for further details), and is a surrogate for future GMPEs that will explicitly address the effect of directivity pulses in a rigorous manner instead of using post hoc correction models.

Ground Motion Selection Methodology

The ground motion selection procedure implemented in this study is based on the GCIM methodology of Bradley (2010, 2012b) and aims to address the aforementioned shortcomings in existing approaches for selecting pulse-like ground motions in the near-fault region. The GCIM procedure considers the contribution of all rupture scenarios affecting the seismic hazard at the site in order to establish the target for ground motion selection. The target is a conditional multivariate distribution of a considered vector of IMs, $\boldsymbol{IM}$, which accounts for various aspects of ground motion severity (i.e. amplitude, frequency content, and duration). A so-called weight vector, w_i, is used to prescribe the relative importance of the considered IMs and calculate the misfit of each prospective ground motion with respect to the target distribution (Bradley 2012a, Tarbali and Bradley 2015b). Forward directivity effects are considered in the target for ground motion selection (via their consideration in the predicted ground motion IMs), and no ad hoc criterion is enforced for selecting a specific proportion of pulse-like records.

Within the framework of the GCIM methodology, the following explicit IMs are considered to establish the target for selection: SA for 19 vibration periods (T= 0.0, 0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 7.5, and 10.0 s); cumulative absolute velocity (CAV); and 5-75% and 5-95% significant durations (D_{s575} and D_{s595}, respectively). These IMs collectively represent amplitude, frequency content, duration, and cumulative ground motion characteristics. The marginal distributions of these IMs are obtained based on the following GMPEs: Boore and Atkinson (2008) for SA; Campbell and Bozorgnia (2010) for CAV; and Bommer et al. (2009) for D_{s575} and D_{s595}. The geometric mean of the two recorded horizontal ground motions is used as the definition of IM in this study (Tarbali and Bradley 2015a). The database of ground motions considered in this study contains 143 directivity records identified by Shahi and Baker (2014) and 6545 non-pulse-like records from NGA-West2 database (Ancheta et al. 2013). Causal parameter bounds are also considered in the ground motion selection based on the magnitude (M_w), source-to-site distance (R_{rup}), and site condition (V_{s30}) bounding criteria recommended by Tarbali and Bradley (2015c).

Characteristics of the Selected Ground Motion Ensembles

In order to empirically investigate the characteristics of selected ground motion ensembles, 78 scenario ruptures are considered which range from M_w =6-7.5, R_{rup}=5-30km, and V_{s30} =200, 400, and 800m/s. The selected rupture scenarios encompass a wide range of causal parameters, with the directivity pulse occurrence probabilities in the range of P_{Dir}=0.05-0.8 (refer to Tarbali and Bradley (2015a) for further details). For each scenario rupture, ground motion ensembles of 20 records were selected; and in order to investigate the variability in the characteristics of selected pulse-like and non-pulse-like records, the selection process is also repeated 20 times for each rupture scenario. Three different 'targets' for ground motion selection were considered. The first two targets are based on considering only SA ordinates in the selection process using a target SA distribution with and without explicit directivity modification (denoted as "case1" and "case2" in the presented results, respectively). The third case involved both explicit consideration of directivity in the SA ordinates as well as multiple non-SA IMs, specifically CAV, D_{s575}, and D_{s595}, (i.e., "case3"). The specific weight vectors adopted in each case are discussed in Tarbali and Bradley (2015b).

As an example of the 78 rupture scenarios, Figure 1(a) illustrates the 16th, 50th, and 84th percentiles of the predicted SA ordinates for a M_w=7.0, R_{rup}=5 km, V_{s30}=400 m/s scenario based on the Boore and Atkinson (2008) GMPE, with and without explicit modification for directivity effects (Shahi and Baker 2011). As shown, directivity consideration results in an increase in the target SA for the range of vibration periods consistent with the pulse period distribution predicted for the corresponding rupture (Tarbali and Bradley 2015a). Figure 1(b)-(d) illustrates the SA ordinates of the selected ground motions (from the specific ensemble with the median number of directivity ground motions, N_{Dir}, among the 20 replicate ensembles) and their corresponding 16th, 50th, and 84th percentiles. As shown by the similarity of the GCIM target and selected ensemble percentiles, the selected records appropriately represent the target SA hazard. In Figure 1, ground motion records classified as 'directivity ground motions' according to Shahi and Baker (2014) are shown as a different color, with the proportion of such selected records noted in the figure captions. Figure 1(b) illustrates that several of the selected ground motions contain notable directivity effects as evident from their long period spectral peaks, even though directivity effects are not explicitly incorporated in the target spectrum. This is due to the fact that the conventional GMPE predictions in the near-fault region are implicitly influenced by directivity records in empirical ground motion databases. Figure 1(c)-(d) also illustrate that considering directivity effects in the target hazard, in general, results in a larger number of directivity ground motions, however, the number of such records in most cases is not close to the predicted directivity pulse occurrence probabilities (this is elaborated on in Figure 3).

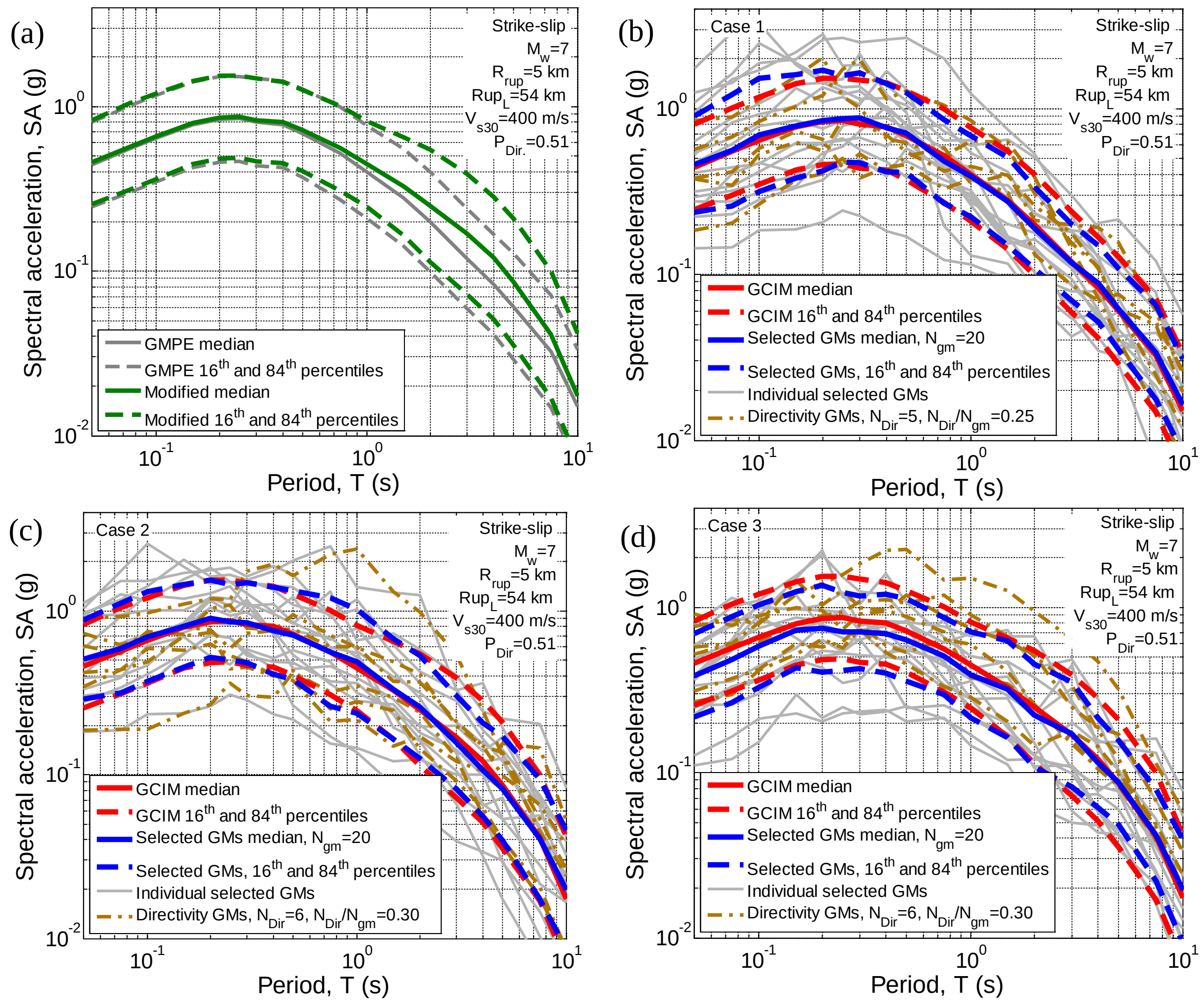

Figure 1: Comparison between the SA ordinates of the selected records and the target hazard for a sample scenario: (a) conventional GMPE in contrast to directivity included predictions; (b)-(c) selection based on only SA ordinates without and with directivity modifications, respectively; (d) selection based on SA, D_{s575}, D_{s595}, and CAV with directivity modifications.

The ground motions depicted in Figure(b)-(c) are selected based on considering only SA ordinates in the selection process. This may result in a biased representation for other important ground motion characteristics such as duration and cumulative IMs. As illustrated in Figure 2(a), for the same rupture scenario as in Figure 1, and as an example among other IMs, statistically significant bias is present in the D_{s575} distribution of ground motions selected based on only SA ordinates (for case2 ensemble) as indicated by the empirical distribution of the ensemble lying ‘outside’ the Kolmogorov-Smirnov (KS) test bounds. This bias in D_{s575} can be resolved by including such an IM in the selection process using an appropriate weight vector in the GCIM methodology (Bradley 2012a, Tarbali and Bradley 2015b). This is shown in Figure 2(a) for case3, for which the ensembles were selected based on SA, D_{s575}, D_{s595}, and CAV. Figure 2(b) presents the pulse period, T_p, distribution of the pulse-like motions from the selected ground motion ensembles in comparison to the predicted T_p distribution from Shahi and Baker (2014). It can be seen that the selected records are generally consistent with the predicted T_p distribution.

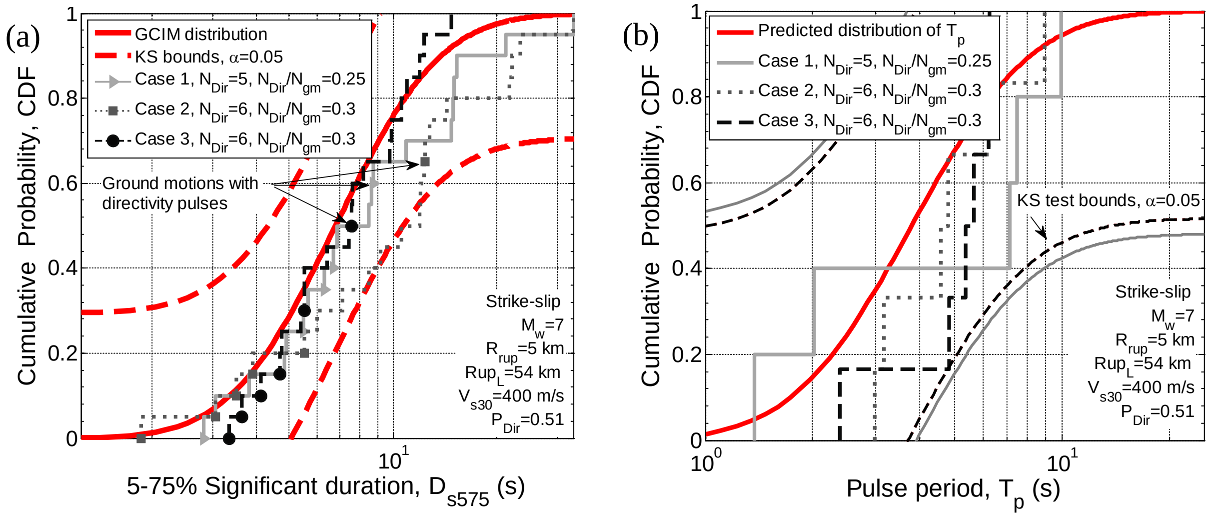

Figure 2: (a) D_{s575}; and (b) pulse period distribution of the selected ensembles (case1-3) for an illustrative rupture scenario (M_w=7.0, R_{rup}=5km, and V_{s30}=400 m/s).

As initially noted, 78 different scenario ruptures were considered to examine the ability of the three different IM targets for ground motion selection within the GCIM methodology. Figure 3 presents the proportion of directivity records in each ensemble (N_{Dir}/N_{gm}) for the considered rupture scenarios with V_{s30}=400 m/s site condition. The box-and-whisker plots illustrate the variation in this proportion of directivity records across the 20 replicates considered. For comparison, the predicted probability of occurrence of directivity pulses, i.e., P_{Dir} (Shahi and Baker 2014) for each rupture scenario is also shown, which it is noted was not considered in the ground motion selection itself. The presented results illustrate that the decreasing trend of P_{Dir} with the increase in R_{rup} is reflected in the selected proportion of pulse-like ground motions. While considering duration and cumulative measures (i.e. case 3 results) generally yields ensembles with a larger number of directivity ground motions, these proportions of the selected ensembles for scenarios with $P_{Dir} > 0.5$ is lower than the predicted value (e.g., M_w=7.0 and 7.5, R_{rup}=5 km scenarios). As discussed in Tarbali and Bradley (2015a), replicate ground motion ensembles (with varying N_{Dir}) result in similar seismic response distributions, regardless of the directivity records proportion in the ensembles. Moreover, ground motions with directivity pulses do not necessarily result in greater seismic demand compared to the non-pulse-like records. As a result, it is advocated here that the selection of ground motions in the near-fault region based on IM properties alone is preferred to that in which the proportion of 'pulse-like' motions is specified a *priori*.

Conclusion

In this paper, the ability of ground motion selection methods to appropriately select records with velocity pulse motions in the near-fault region was examined. Particular attention was given to ground motion selection which is explicitly based on ground motion intensity measures (IMs), including pseudo-acceleration response spectrum, duration, and cumulative measures; rather than a focus on implicit parameters (i.e. pulse or non-pulse classifications) that are conventionally used to heuristically distinguish between the near-fault and far-field records. The selection process is based on the generalized conditional intensity measure (GCIM) approach which addresses the shortcomings of existing methods for selecting forward directivity ground motions. Forward directivity effects were considered in the target IM distributions at the seismic hazard analysis stage, and no ad hoc criterion was enforced for selecting pulse-like records. Example applications were presented here only for scenario seismic hazard analysis cases with different rupture characteristics, source-to-site geometry, and site conditions – probabilistic seismic hazard analysis-based results are shown in Tarbali and Bradley (2015a). It was shown that selection based on an appropriate set of IMs will indirectly lead to ground motion ensembles with the appropriate proportion of forward directivity motions, especially for scenario ruptures with pulse occurrence probabilities less than 0.5, while further developments are needed in directivity models and ground motion prediction equations for large magnitude scenario ruptures (i.e., $M_w \geq 7.0$).

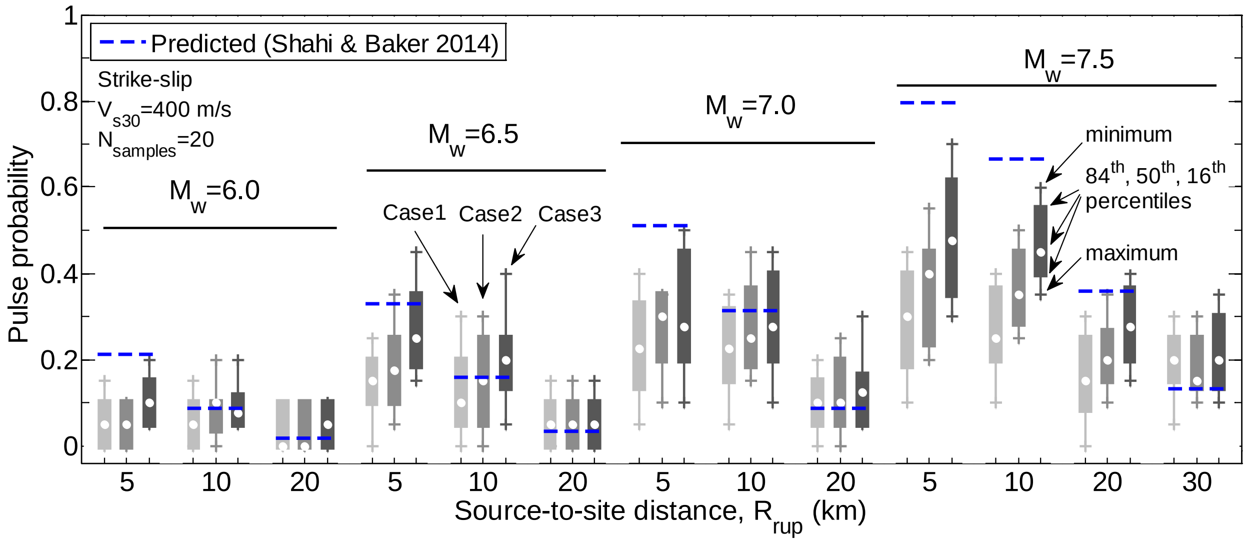

Figure 3: Pulse probability represented by the selected ground motion ensembles for the considered strike-slip rupture scenarios with V_{s30}=400 m/s site condition. The results for case1,2 and 3 are shown by separate box-and-whisker colors as annotated.

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