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Trade-offs in ground motion selection techniques for collapse assessment of structures

J.W. Baker[1]

[1] Civil & Environmental Engineering, Stanford University, Stanford, USA

Abstract. When performing nonlinear dynamic analysis to determine the collapse capacity of a structure, decisions regarding ground motion selection play a prominent role in the quality of the results. A number of studies have shown that collapse capacities can be over- or under-estimated by significant factors if inappropriate ground motions are utilized for analysis. This paper presents a review of recent findings regarding the role of ground motions in accurate collapse assessment, describes properties of ground motions known to affect collapse capacity, and discusses advantages and disadvantages of various options for ground motion selection and scaling. In particular, multiple stripe analysis (MSA) and incremental dynamic analysis (IDA) are compared. Multiple stripe analysis allows the analyst to use differing suites of ground motions at each ground motion intensity level; this allows for differences in anticipated properties of low-intensity and high-intensity motions to be captured via ground motion selection, but requires additional effort in ground motion selection and structural analysis. Incremental dynamic analysis, on the other hand, uses a single suite of ground motions rescaled to a number of intensity levels; this requires only a single standardized suite of ground motions, and reducing required analysis effort. But the benefits of the simpler procedure are counteracted by a loss in accuracy of the result.

Keywords: Ground motion selection, collapse, hazard, spectral shape, epsilon, duration

1 INTRODUCTION

A number of structural performance assessment procedures use collapse capacity estimates obtained from dynamic structural analysis (Applied Technology Council 2012, 2013; Federal Emergency Management Agency 2009), and collapse capacities of structures are frequently studied in other contexts as well (e.g., Deierlein and Haselton 2005; Eads et al. 2013; Elwood and Moehle 2008; Goulet et al. 2007; Ibarra and Krawinkler 2005; Liel et al. 2011; Shome 1999; Zareian et al. 2010). These studies involve careful numerical modelling in order to predict structural collapse, and they also require development of input ground motions for use in the analysis. This paper discusses the topic of ground motion selection for the purpose of collapse capacity estimation. The selection of ground motions for assessment of collapse risk is particularly important due to the high amplitude of shaking necessary to collapse most engineered structures. Literature quantifying the importance of ground motion selection for this problem is reviewed, and noted important guidance for analysts is summarized. The paper also discusses trade-offs among candidate approaches for developing input ground motions, with regard to improved realism versus increased effort.

A goal of many of the above analyses procedures is to quantify the collapse capacity of a structure using a fragility function specifying the probability of collapse given a ground motion with amplitude measured by an Intensity Measure (*IM*) such as spectral acceleration at a given period. Fragility functions are often obtained by performing Incremental Dynamic Analysis (IDA) using a suite of ground motions, and counting the fraction of the ground motions causing collapse at each *IM* level of interest, as illustrated in Figure 1. Collapse risk of the structure is then evaluated by combining information regarding the ground motion hazard, which quantifies the likelihood of observing ground motions with various *IM* levels, with the fragility curve. The hazard information could be as simple as the *IM* level associated with "Maximum Considered Earthquake" shaking, or more sophisticated and provide a full ground motion hazard curve and deaggregation information indicating other properties of ground motions likely to be observed at the site. Within this general collapse assessment procedure, there are two ways of viewing the role of ground motions, with differing implications regarding ground motion selection procedures.

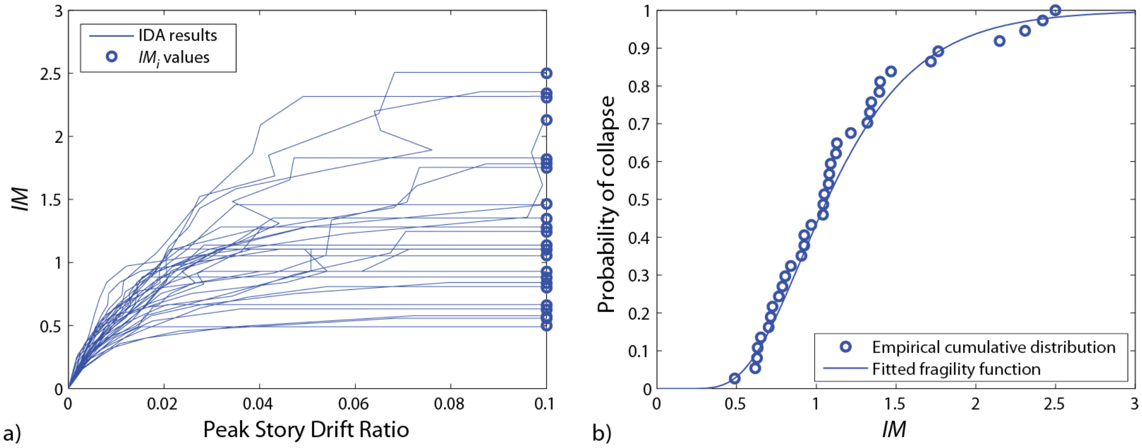


Figure 1. (a) Illustration of Incremental Dynamic Analysis results. (b) *IM* values at collapse as observed from the IDA results, and a collapse fragility function fitted to the data (from Baker 2013).

2 TWO PERSPECTIVES ON THE ROLE OF GROUND MOTIONS

Ground motions for the collapse assessment process can be viewed from one perspective as "dynamic loading protocols." That is, the ground motions are treated as a standardized set of loading conditions to which a structure is subjected, in order to investigate its response. This approach makes the assessment procedure much simpler, as a standardized set of ground motions can be used in all analysis cases, saving the effort of selecting new ground motions and potentially facilitating "fair" comparisons of collapse capacity across building classes and locations (though, as discussed below, this may not actually be fair in some cases).

If this first perspective is adopted, generic suites of ground motions are appropriate for use in collapse prediction. There are a number of such sets available today. The "SAC ground motions" (Somerville et al. 1997b) and "LMSR records" (Krawinkler et al. 2003) have been used for a number of years by many researchers and analysts. More recently, the FEMA P695 project (Federal Emergency Management Agency 2009) developed two suites of standardized ground motions that are recommended for use with that project's assessment procedure and have since been used in a number of other studies. The PEER Center has also developed several standardized ground motion sets (Baker et al. 2011) for use in that Center's research activities, and provided publically for other users. These sets of motions are popular because they allow users to obtain ground motions with a minimum amount of effort. They are also popular for cases where a number of building types are being studied, or where there is no specific site of interest.

The conceptual problem with use of generic ground motions, however, is that they lead to a building being considered equally safe if it is located in New Madrid, Seattle or Los Angeles, if those sites had similar hazard (defined with regard to the *IM* used to specify the collapse fragility). The question is whether the differences in the anticipated properties of strong ground shaking at those varying locations need to be further accounted for in a collapse risk assessment.

In an alternate perspective, the ground motions are viewed as our best estimate of what future ground motions at the site of interest, and with the *IM* level of interest, might look like. With this perspective, the ground motions for a given analysis should be representative of ground motions a specific building may actually see. Further, low-amplitude ground motions generally have different properties than high-amplitude motions, and so unique motions should be used at each intensity level of interest, as illustrated in Figure 2. Such an analysis is sometimes referred to as Multiple Stripe Analysis (MSA). The use of such an approach will make the analysis results more predictive of building behavior at that site. The drawback is that it requires site-specific motions to be selected for each analysis case. This requires more information about the site to be known, and requires more analyst effort.

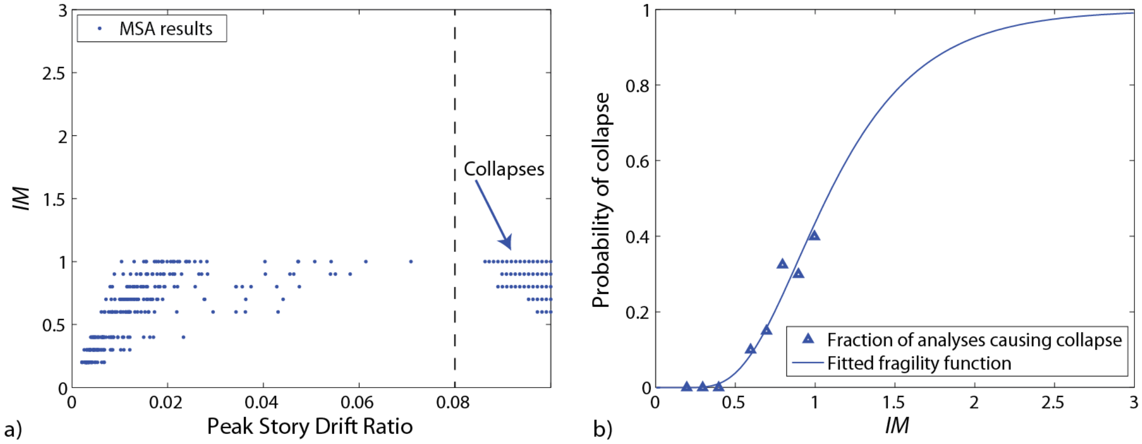


Figure 2. Illustration of Multiple Stripes Analysis for collapse capacity fitting (from Baker 2013). (a) Results from dynamic analyses using differing ground motions at each IM level; analyses causing collapse are plotted at Peak Story Drift Ratios of greater than 0.08, and are offset from each other to aid in visualizing the number of collapses. (b) Observed fractions of collapse at each *IM* level, and a fitted fragility function.

Site specific ground motions are more representative of ground motions a specific building may actually see. For example, near-fault sites are more likely to experience ground motions with short durations and large velocity pulses; sites in subduction regions, conversely, are more likely to experience long-duration shaking. And sites with stiff versus soft near-surface materials will experience different types of shaking. Finally, for all sites, high-amplitude ground motions are likely to have different properties than low-amplitude ground motions, raising concerns regarding the scaling of a single suite of generic motions to represent shaking at a range of amplitudes. Recognizing the impact of these issues, a number of codes and guidelines for assessment of individual structures recommend that some or all of these anticipated properties be considered when selecting ground motions for structural assessment (see, e.g., NIST 2011 for a summary of guidance from a number of such documents).

3 IMPORTANT PROPERTIES OF GROUND MOTIONS FOR COLLAPSE ASSESSMENT

The distinction between generic and site-specific motions is only important if it is known that differences in ground motions would lead to differences in inferred collapse capacity of the structure of interest. In the following section, a number of ground motion properties will be discussed, with respect to their impact on structural response and collapse capacity.

3.1 Elastic response spectra and spectral shape

The term "spectral shape" is often used to refer to the relative amplitudes of spectral accelerations of a ground motion at differing periods. This property is relevant for collapse assessment because, if the ground motion's intensity measure is defined as a spectral acceleration value at a single period, then spectral shape will quantify spectral accelerations at other periods conditional on that *IM*. To be more specific, a common choice of *IM* is spectral acceleration at the elastic first-mode period of the structure of interest. In that case, spectral shape can indicate the relative amplitude of shorter-period spectral values that are predictive of higher-mode responses, or longer-period spectral values that are seen to be predictive of nonlinear response when the structure has softened and its "effective period" has lengthened (Baker and Cornell 2008).

The expected spectral shape of a ground motion is known to vary with location due to differences in causal earthquake magnitudes and distances, and differences in local site conditions, but it also varies strongly as the ground motion amplitude of interest changes (Baker and Cornell 2006). To illustrate, consider the ground motions shown in Figure 3. The heavy dashed line shows a uniform hazard spectrum (UHS) with 2% probability of exceedance in 50 years for a site in Riverside, California (see Baker 2011 for more details on this analysis). Deaggregation of the seismic hazard results indicates that the high-amplitude ground motions associated with the UHS are most likely to be caused by magnitude 7 earthquakes at a distance of 12 km, and ground motions whose response spectra are approximately two standard deviations larger than typical (median) response spectra for that earthquake scenario (i.e., "ε equals 2"). This two-standard-deviation condition results from considering a UHS with a probability of exceedance that it is much smaller than the probability of occurrence of the earthquake scenario contributing most to hazard.

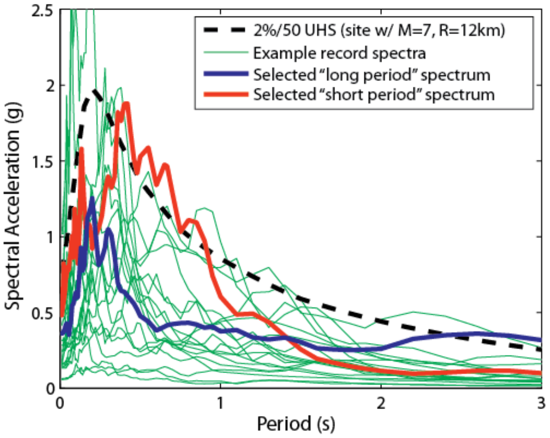


Figure 3. Target response spectrum for an example site in Riverside, California, and response spectra of ground motions from earthquakes consistent with magnitudes and distances of ground motions expected at that site.

Also shown in Figure 3 are response spectra from real ground motions recorded from events with magnitude = 7 and site to source distance = 12 km. The average of these spectra lie much lower than the UHS (in fact, their median is quite close to the median spectrum expected for such a scenario), but at almost all periods there are one or two ground motions whose spectra are as high as the UHS. The important additional detail, however, is that no single ground motion has a spectrum has high as the UHS across all periods shown in the figure. Two ground motions with high response spectra at long periods and short periods are highlighted in this figure, to illustrate that they do not stay comparably high at all periods. This is important because it implies that ground motions with high amplitude spectra at, for example, 2.5 seconds, are more likely to have a response spectrum like that of the "long period" motion in Figure 3 than to have a spectrum like the UHS (the latter associated with much higher demands at shorter periods and thus more likely to cause collapse of a structure sensitive to short-period excitations).

Most investigations of the causes of differences in spectral shapes, and the resulting impact on collapse risk, has focused on the role of magnitude, distance and ε. Site conditions, quantified via near-surface shear wave velocity or depth of sedimentary basins, also have a strong relationship with spectral shape. This means that buildings at very similar locations, but on sites with differing soil conditions, will likely experience ground motions with notably different spectral shape and thus notably different collapse capacities (Liel et al. 2013).

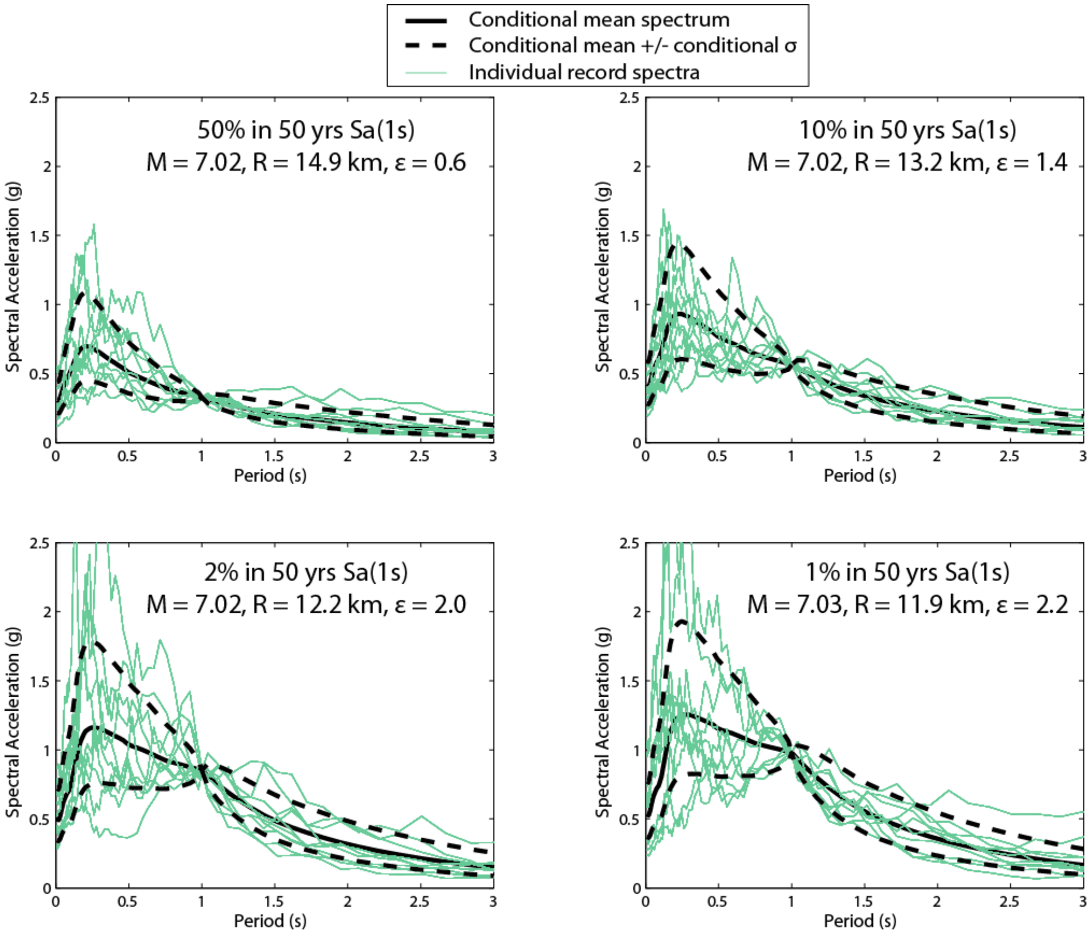


Figure 4. Conditional-spectrum-based ground motion selection at four intensities for an example site in Riverside.

Spectral shape can be quantified via the Conditional Spectrum and used to select ground motions with appropriate response spectra for a given site and *IM* value (Jayaram et al. 2011). Figure 4 shows Conditional Spectra (quantified by the mean and standard deviation of spectral values), conditional on one-second spectral acceleration (i.e., *IM* = *Sa*(1s)) values at four amplitudes associated with four exceedance probabilities. Response spectra of ground motions selected to match those targets are also shown. The mean values of magnitudes, distances and ε' s associated with occurrence of these spectral amplitudes are noted in each sub-figure. As the *Sa*(1s) amplitudes increase across these subfigures, the associated spectral shapes vary in a way that can be captured via site-specific ground motion selection, but cannot be captured using generic ground motion sets.

3.2 Velocity pulses and near-fault directivity

Another ground motion property known to influence structural collapse capacity is the presence of a strong velocity pulse (e.g., Bertero et al. 1978; Hall et al. 1995; Alavi and Krawinkler 2001; Sehhati et al. 2011, among many others). Often caused by near-fault directivity (Somerville et al. 1997a; Somerville 2003), these pulses place large demands on structural systems, especially if the period of the pulse is slightly longer than an elastic structural period, in a way that is not well quantified by measuring spectral acceleration at the elastic period of interest. An illustration of observations of these pulses at near-fault sites is shown in Figure 5.

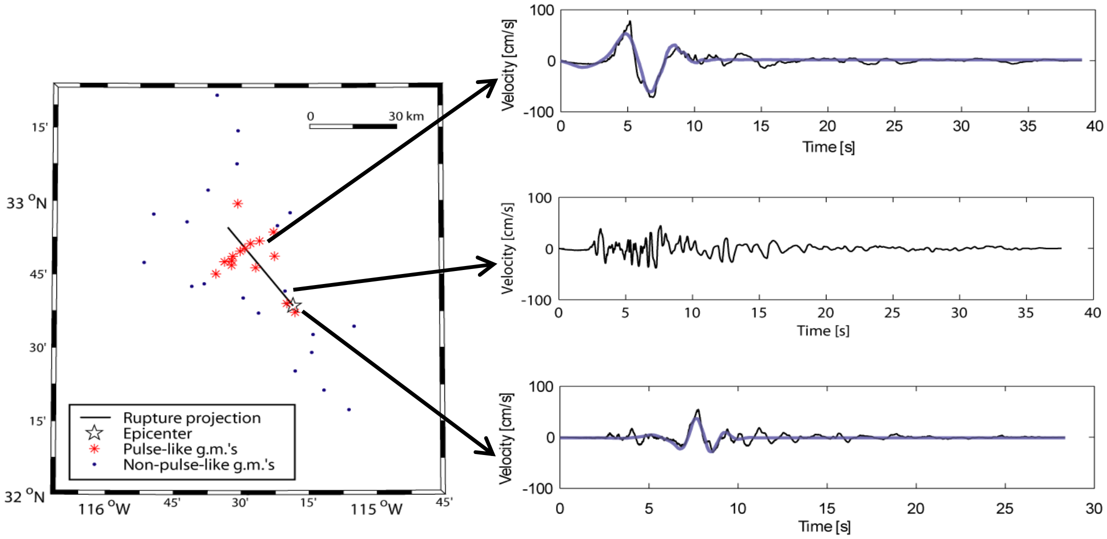


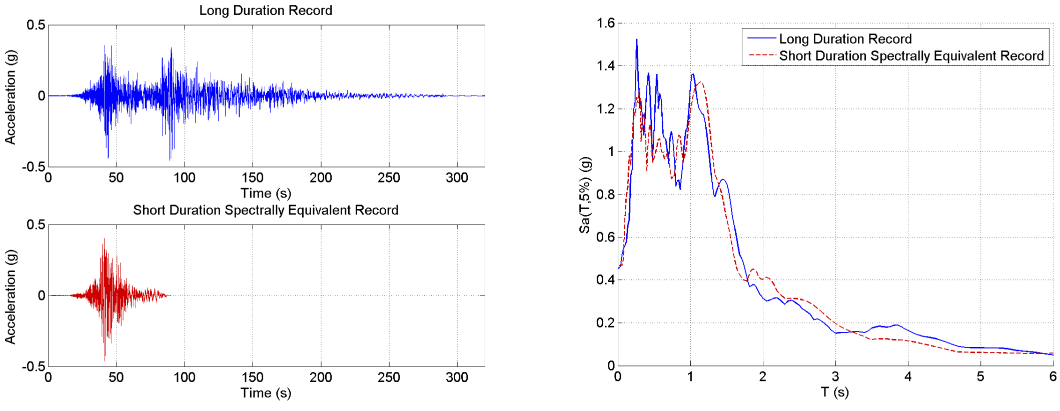
Figure 5. A map of the 1979 Imperial Valley earthquake rupture and locations of strong motion recording instruments (left), and plots of three fault-normal near-fault ground motion recordings (right), of which the top and bottom motion show strong velocity pulses.

There are a number of statistical models for predicting the probability of occurrence of these pulses in a given earthquake scenario (e.g., Iervolino and Cornell 2008; Mena and Mai 2010; Shahi and Baker 2011). Champion and Liel (2012) recently performed collapse capacity studies as a function of pulse parameters, to provide quantitative information regarding the importance of this property with respect to collapse risk. They found that velocity pulses resulted in a factor of 3 or more change in median collapse capacity for the example structure, and when integrated with the probabilities of observing velocity pulses of varying periods at a given site, can result in notable shifts in overall collapse risk of structures at near-fault locations.

3.3 Duration

Several recent studies of ground motion duration have quantified a substantial effect of long-duration shaking in reducing the collapse capacity of structures (Chandramohan et al. 2013; Foschaar et al. 2012; Raghunandan and Liel 2013). An example of these findings, Chandramohan et al. (2013) developed two sets of ground motions with differing durations but equivalent response spectra, so that differences in collapse capacities obtained from the two sets could be attributed to duration. Two spectrally equivalent ground motions from that study are shown in Figure 6. Suites of 158 spectrally equivalent motions were compiled, and Incremental Dynamic Analysis of a steel moment frame structure was performed using each suite, to obtain the collapse capacities shown in Figure 7. The long duration ground motions produced a collapse capacity curve with a 40% smaller median than the short duration motions (Sa(1.5s) = 0.53g versus 0.90g). Similarly, Raghunandan and Liel (2013) predicted a

40% decrease in median collapse capacity for a modern concrete frame located in Seattle versus San Francisco, due to the much longer duration of shaking expected for ground motions from large subduction earthquakes near Seattle.



(a) (b)

Figure 6. Example of a long duration and short duration spectrally equivalent pair of ground motions. (a) Time series of two spectrally equivalent ground motions, and (b) the response spectra of those motions (from Chandramohan et al. 2013).

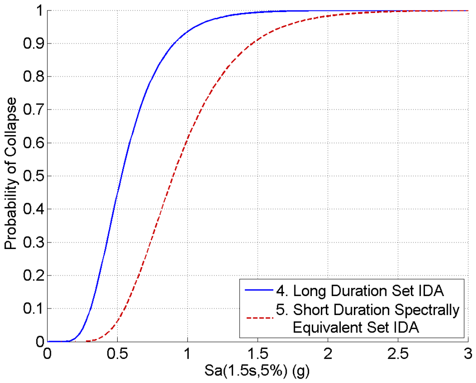


Figure 7. Collapse fragility curves obtained from Incremental Dynamic Analysis using long duration and short duration spectrally equivalent sets of ground motions (from Chandramohan et al. 2013).

These findings are in contrast to many earlier studies that found little correlation between shaking duration and peak structural response parameters, but which generally considered only moderately nonlinear structures and simple numerical models that did not capture degradation of the structure during long-duration shaking (e.g., Hancock and Bommer 2006; Iervolino et al. 2006). For collapse assessment of structures using modern numerical models, the recent results discussed above clearly supersede the earlier studies and indicate the significant potential impact of duration.

4 CONCLUSIONS AND DISCUSSION

This paper presented a discussion of important properties of ground motions with respect to structural collapse assessment, and tradeoffs in the accuracy and practicality of various collapse assessment procedures. Two approaches for treatment of ground motions were discussed. The first approach is to use general suites of ground motions as a “dynamic loading protocol” for use with all structures and locations of interest, and perform Incremental Dynamic Analysis to estimate a collapse capacity. This is a simple procedure and doesn’t require *a priori* information regarding building location, which is important for general screening procedures when site-specific analyses are not being performed. The second approach is to use ground motions selected specifically for each site and ground motion amplitude of interest, using a Multiple Stripes Analysis approach. The latter approach is superior for quantifying the collapse risk of a structure at a specific location, but requires site-specific information. Further, if applied inconsistently, site specific selection procedures may influence conclusions when multiple parties are producing the comparisons of collapse risk.

The distinction between these approaches is important because a number of ground motion properties have the potential to affect collapse capacity for a given structure and are known to vary from location to location. Further, the impact on collapse capacity is large enough that it can significantly affect the resulting predictions of collapse risk. For example, Haselton et al. (2011) found a factor of 23 change in predicted collapse rate for an 8-story concrete frame building in Los Angeles when the spectral shape was based on site-specific analysis, relative to when the generic FEMA P695 ground motions were used. And Raghunandan and Liel (2013) predicted a 40% decrease in median collapse capacity for a modern concrete frame located in Seattle versus San Francisco, due to the longer duration of shaking expected for intense ground motions in Seattle.

Site-specific ground motion issues matter less for collapse screening procedures where the goal is to obtain a *relative* ranking of collapse risk for a population of buildings with similar seismic hazard, such as all nonductile reinforced concrete buildings in the Los Angeles region (Anagnos et al. 2008). But site-specific motions may still be important to consider even in these cases. For example, some buildings' failure mechanisms could be susceptible to short-duration pulses, while others' weaknesses may arise under high numbers of loading cycles in a long duration earthquake. If that is the case, using ground motions unrepresentative of motions at a given site may preferentially trigger certain failure mechanisms while hiding others, thus leading to incorrect relative rankings of building types with differing deficiencies. This potential effect has not yet been quantified in a numerical study, but it may be significant and so should be carefully considered when using generic ground motions for collapse assessment.

When considering treatment of ground motions for general collapse assessment procedures, an option that bridges the above two approaches is to use generic ground motions for structural analysis, but modify the resulting collapse capacities after the fact to reflect anticipated impacts of ground motion properties at a specific site of interest. This option has the benefit of avoiding the effort of site-specific ground motion selection, but at the cost of relying on approximate corrections to account for effects that could be captured directly via a refined treatment of ground motions. This approach was developed in the FEMA P695 project to account for the anticipated effect of variation in spectral shape from one location to another (Haselton et al. 2011). Even so, the model developed in that project includes no adjustments for duration, site conditions or directivity, and it was calibrated only for frame structures. A more general model would be needed for this approach to be applied generally. Development of a general model of this type may be a worthwhile topic of future research to facilitate collapse risk screening procedures.

It is clear that there is no single best approach for treatment of ground motions in all analysis circumstances. Development of consensus regarding appropriate approaches in specific circumstances will depend upon careful articulation of the objectives of collapse assessment methodologies. Additionally, progress will depend on further research to quantify the impact of various ground motion properties on collapse risk across a range of seismic environments and for a range of building types.

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