EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS
Earthquake Engng Struct. Dyn. 2006; **35**:1077–1095
Published online 12 April 2006 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/eqe.571

Spectral shape, epsilon and record selection

Jack W. Baker*,† and C. Allin Cornell‡

Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, U.S.A.

SUMMARY

Selection of earthquake ground motions is considered with the goal of accurately estimating the response of a structure at a specified ground motion intensity, as measured by spectral acceleration at the first-mode period of the structure, $Sa(T_1)$. Consideration is given to the magnitude, distance and epsilon (ε) values of ground motions. First, it is seen that selecting records based on their ε values is more effective than selecting records based on magnitude and distance. Second, a method is discussed for finding the conditional response spectrum of a ground motion, given a level of $Sa(T_1)$ and its associated mean (disaggregation-based) causal magnitude, distance and ε value. Records can then be selected to match the mean of this target spectrum, and the same benefits are achieved as when records are selected based on ε. This mean target spectrum differs from a Uniform Hazard Spectrum, and it is argued that this new spectrum is a more appropriate target for record selection. When properly selecting records based on either spectral shape or ε, the reductions in bias and variance of resulting structural response estimates are comparable to the reductions achieved by using a vector-valued measure of earthquake intensity. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: ground motion selection; record selection; intensity measure (IM); uniform hazard spectrum (UHS)

INTRODUCTION

Selection of recorded earthquake ground motions is an important consideration when assessment of structures is based on dynamic analysis. Careful ground motion selection can achieve the same reduction in bias and variance of structural response as is gained by more advanced measures of ground motion intensity, while allowing the user to process the records using simple measures of intensity such as elastic spectral acceleration [1, 2]. The ground motion parameter epsilon (ε) has been shown to be an important predictor of structural response as

*Correspondence to: Jack W. Baker, Terman Engineering Center, Room 234, Stanford University, Stanford, CA 94305, U.S.A.
†E-mail: bakerjw@stanford.edu
‡E-mail: cornell@stanford.edu

Contract/grant sponsor: National Science Foundation; contract/grant number: EEC-9701568

Received 1 December 2005
Revised 15 January 2006
Accepted 21 January 2006

part of a vector-valued intensity measure (IM) [3], but the relationship between that finding and the effect of selecting ground motions based on their ε values has not yet been examined in detail. Here we consider the issue more thoroughly, and identify record properties that should be considered when selecting ground motions for analysis. These criteria are considered in the context of probabilistic assessment of structures, where both the ground motion hazard and the response given the ground motion are quantified in a formal probabilistic manner. It will be seen that consideration of ε values when selecting records is important, as ε is related to spectral shape, and thus a predictor of structural response.

Alternatively, a method is proposed for developing a target spectrum that accounts for the magnitude (M), distance (R) and ε values likely to cause a given target ground motion intensity at a given site. The spectrum obtained in this way is termed a *conditional mean spectrum*, *considering* ε (CMS-ε). This target spectrum criterion possibly widens the range of acceptable records for analysis because the selected records do not necessarily have appropriate magnitude, distance and ε values, but rather the records need only have a spectral shape that matches the mean spectrum from the causal event. The proposed target spectrum is compared to a uniform hazard spectrum (UHS), and seen to be superior for obtaining unbiased estimates of structural response. The CMS-ε is similar to target response spectra used in the nuclear safety industry [4–6], except that the effect of ε has been incorporated here as well, given the new findings about the relationship between ε and spectral shape [3].

For the above reasons, it is suggested that when selecting earthquake motions for dynamic structural analysis, efforts should be made to find records with appropriate ε values; this appears to be more important than finding records with appropriate magnitude and distance values. Alternatively, one could select ground motions based on their similarity with the target CMS-ε, which accounts for the effect of causal magnitudes, distances and epsilons. Using these selection criteria, more efficient estimates of structural response can be obtained, and potential biases in estimated structural response can be avoided. These results are relevant for estimating the mean response at a given ground motion level (as used in, e.g. Reference [7]) as well as probabilistic assessments of structural response (as used in, e.g. References [8, 9]).

THE EFFECT OF EPSILON ON SPECTRAL SHAPE

The ground motion parameter ε has been identified as an indicator of spectral shape [3]. Formally measured using $Sa(T_2)/Sa(T_1)$ for some T_1 and T_2, spectral shape indicates the relative values of spectral accelerations at other periods, given Sa at T_1. The parameter ε is a measure of the difference between the spectral acceleration of a record and the mean of a ground motion prediction equation at the given period. The relationship between ε and spectral shape is demonstrated in this section by examining patterns seen in a large set of recorded ground motions taken from the PEER Strong Ground Motion Database [10]. This link between ε and spectral shape justifies later conclusions regarding record selection. All available records from this database that met the following criteria were selected:

1. The site was classified as stiff soil: USGS class B-C or Geomatrix class C-D.
2. The recording was made in the free field or the first storey of a structure.
3. The earthquake magnitude was greater than 5.5.
4. The source-to-site distance was less than 100 km.

5. The vertical and both horizontal components of the recording were available and each had high-pass filter corner frequencies less than 0.2 Hz and low-pass filter corner frequencies greater than 18 Hz.

These criteria were used to identify records believed to be most relevant for engineering purposes. Additionally, records from the well-recorded Chi-Chi earthquake were omitted to ensure that no single earthquake was the source of a significant fraction of the records in the database. A total of 191 recordings met the above criteria, resulting in 382 individual horizontal ground motion components available for use (record details are given in Reference [2, Table A.5]). These records were examined to search for a relationship between ε and spectral shape. First, ε values were computed for each record at a range of periods using the ground motion prediction model of Abrahamson and Silva [11]. The structure studied below has a first-mode period of 0.8 s, so here the ε values at 0.8 s are considered. The 20 records with the largest ε values at a period of 0.8 s were identified (these records have ε values greater than 2.25), as well as the 20 closest to zero (these records have ε values between -0.06 and 0.06) and the 20 with the smallest ε values (these records have ε values less than -2.25). The spectra of the records with large ε values are scaled to have the same $Sa(0.8\,\mathrm{s})$ value and plotted in Figure 1(a), along with their geometric mean; the records are scaled to $Sa(0.8\,\mathrm{s}) = 0.5g$, but the relative shapes of the spectra are not affected by actual value used. In Figure 1(b), the spectra with small ε values are shown, along with their mean. In Figure 2(a), the geometric means of all three record sets are displayed. It is clear that the average shapes of these record sets differ, even though each set has a wide range of magnitudes and distances, and the distribution of magnitude and distance values of the records does not differ appreciably among the sets. The same effect is observed in Figure 2(b) where the exercise is repeated at a period of 0.3 s (the records selected and the resulting spectral shape depend upon the period, because ε values vary by period). This indicates that ε is accounting for differences in spectral shape, providing further empirical evidence for this previously observed effect [3]. Note that the most important distinction among these three sets is that between positive-ε

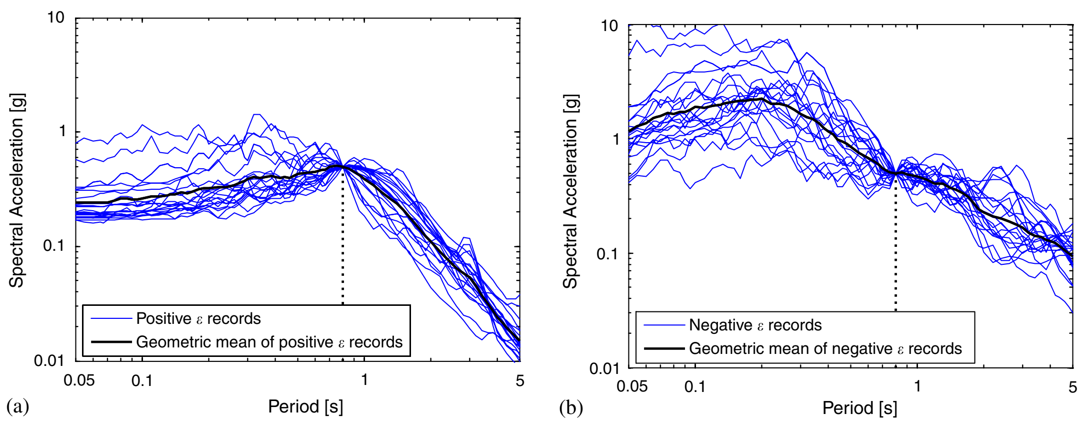


Figure 1. (a) Response spectra of records with the 20 largest ε values at 0.8 s, and the geometric mean of the set, after scaling all records to $Sa(0.8\,\mathrm{s}) = 0.5g$; and (b) response spectra of records with the 20 smallest ε values at 0.8 s, and the geometric mean of the set, after scaling all records to $Sa(0.8\,\mathrm{s}) = 0.5g$.

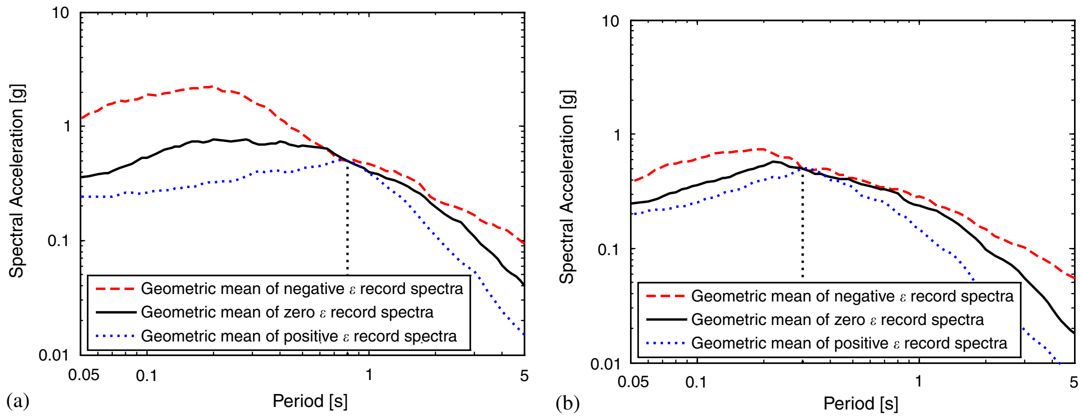


Figure 2. (a) The geometric mean of response spectra for negative-ε, zero-ε and positive-ε record sets, after each record's spectrum has been scaled to $Sa(0.8\,\text{s}) = 0.5g$; and (b) the geometric mean of response spectra for negative-ε, zero-ε and positive-ε record sets, after each record's spectrum has been scaled to $Sa(0.3\,\text{s}) = 0.5g$.

records and zero-ε records, because the former are associated with long-return-period ground motions while the latter are associated with typical record sets chosen without regard to ε values.

It is widely known that for records with the same $Sa(T_1)$ value, spectral shape will affect the response of multi-degree-of-freedom and non-linear structures, because spectral values at other periods affect response of higher modes of the structure as well as non-linear response when the structure's effective period has lengthened. It is also recognized that magnitude and distance can affect the spectral shape of records. In Reference [3], however, it was seen that ε also affects spectral shape, and that its effect is at least as great as that of magnitude or distance. In the next section, knowledge of the effect of M, R and ε on structural response will be used as a guide when selecting records for non-linear analysis.

A PREDICTIVE MODEL FOR SPECTRAL SHAPE

A new target spectrum can now be developed, accounting for the relationship between ε and spectral shape. To develop this target spectrum, PSHA is used to find the $Sa(T_1)$ value corresponding to the target probability of exceedance at the site, denoted $Sa(T_1)^*$. Disaggregation can then be used to find the mean of the M, R and ε values (denoted $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}$) that cause occurrence of the $Sa(T_1)^*$ level [12]. $\overline{M}$ and $\overline{R}$, in turn, determine the means and standard deviations of response spectral values for all periods via ground motion prediction models, and $\overline{\varepsilon}$ specifies the number of standard deviations away from the mean the ground motion is *at the first-mode period*, T_1. Given knowledge of the mean ε at T_1, denoted $\overline{\varepsilon}(T_1)$, the conditional distribution of Sa values at other periods can be calculated using only the disaggregation data and knowledge of correlations of ε values at a range of periods, as will be shown below.

This scheme for developing a target spectrum follows closely from procedures to develop target spectra for analysis of nuclear facilities [4–6], except that those methods incorporate only the causal M and R values from disaggregations; here, the effect of ε is incorporated as well. A similar idea was used previously to develop target response spectra that accounted partially for the effect of ε [13].

The mean value of the target response spectrum based on $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}$ can be computed in the following manner: as was outlined in Reference [3], given certain assumptions the conditional mean of the response spectrum can be computed using the following equation:

$$\mu_{\ln Sa(T_2)|\ln Sa(T_1)=\ln Sa(T_1)^*} = \mu_{\ln Sa}(\overline{M},\overline{R},T_2) + \sigma_{\ln Sa}(\overline{M},T_2)\rho_{\ln Sa(T_1),\ln Sa(T_2)} \cdot \overline{\varepsilon}(T_1) \tag{1}$$

where $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}(T_1)$ come from disaggregation given $Sa(T_1)=Sa(T_1)^*$. The terms $\mu_{\ln Sa}(\overline{M},\overline{R},T_2)$ and $\sigma_{\ln Sa}(\overline{M},T_2)$ are the marginal mean and standard deviation of $\ln Sa$ at T_2, obtained from a ground motion prediction (attenuation) relationship (e.g. Reference [11]). Equation (1) is, in fact, an approximation obtained by substituting the mean values $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}$ for the random values of M, R and ε obtained from disaggregation. When the ground motion hazard is dominated by a single magnitude and distance, as is the case for many coastal California sites and certain Central or Eastern U.S. sites near Charleston or New Madrid, the approximation is nearly exact. A detailed investigation into the approximation [2, Appendix E], suggests the error introduced by Equation (1) is less than about 10% in all realistic cases. This upper-bound error occurs when the ground motion hazard has equal contributions from two earthquake sources with significantly different spectral shapes (e.g. a nearby fault producing small magnitude events, and a distant fault producing large magnitude events). In this case, the more complicated exact equation for the conditional mean spectrum can be used if the potential error from Equation (1) is deemed to be unacceptable [2, Appendix E]. Further, when substituting $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}$ into Equation (1), one does not necessarily obtain exactly the target $Sa(T_1)$ value back again. This can be addressed by re-assigning $\overline{\varepsilon}$ to the ε value that results in a prediction of the $Sa(T_1)$ target value; the modification will be small and this is consistent with the treatment of ε by McGuire [12]. To complete the calculation of Equation (1), the following prediction for $\rho_{\ln Sa(T_1),\ln Sa(T_2)}$, developed from regression on empirical observations [14], is also needed:

$$\rho_{\ln Sa(T_1),\ln Sa(T_2)} = 1 - \cos\left(\frac{\pi}{2} - \left(0.359 + 0.163 I_{(T_{\min}<0.189)} \ln\frac{T_{\min}}{0.189}\right)\ln\frac{T_{\max}}{T_{\min}}\right) \tag{2}$$

where $T_{\min}$ and $T_{\max}$ are the smaller and larger of T_1 and T_2, respectively, and $I_{(T_{\min}<0.189)}$ is an indicator function equal to 1 if $T_{\min}<0.189$ s and equal to 0 otherwise. Note that with the above information, conditional variances of the response spectrum could also be easily computed, but they will not be used here.

Conditional mean spectra computed using Equation (1) are shown in Figure 3 for three hazard levels, using of $Sa(0.8\,\text{s})$ as the IM. The $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}$ associated with each hazard level are labelled in the figure. Note that the spectra have slight peaks at 0.8 s, and that the peak becomes more prominent as the $Sa(0.8\,\text{s})$ level (and the associated $\overline{\varepsilon}$) increase. This is a reflection of the phenomenon observed in Figures 1 and 2.

It is reasonable to assume that M, R and ε are important to structural response only indirectly as proxies for spectral shape, and that spectral shape is the record property directly affecting structural response among records with the same $Sa(T_1)$; this assumption will be further

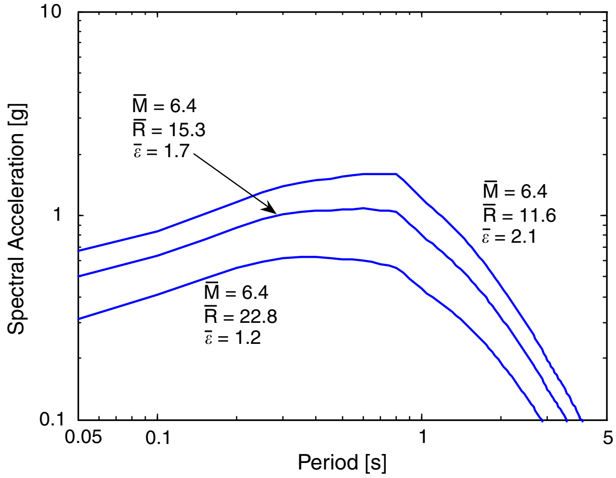


Figure 3. Mean values of the conditional response spectrum for a site in Van Nuys, California, given occurrence of $Sa(0.8\,\mathrm{s})$ values exceeded with 2, 10 and 50% probabilities in 50 years, and the associated $\overline{M}$, $\overline{R}$, $\bar{\varepsilon}$ from PSHA disaggregation.

justified below. Thus, rather than trying to match target M, R and ε values when selecting records, one might use M, R and ε to determine a target spectral shape using Equation (1), and select records based on this target alone. This should increase the number of available records, because some records with incorrect M, R or ε values may have the 'correct' spectral shape.

Only the mean value of the conditional spectrum is used here as the target, rather than accounting for the entire conditional distribution. This is done under the justification that $Sa(T_1)$ is the primary predictor of structural response, and spectral values of other periods are of secondary importance. Thus, $Sa(T_1)$ will be accounted for in a fully probabilistic manner by using a ground motion hazard curve, and the other spectral values will be accounted for through their conditional means. This approach follows probabilistically based load combination rules used in practice elsewhere (e.g. Reference [15, pp. 17–18]). In the sections below, this conditional spectrum defined by Equation (1) is termed the *conditional mean spectrum, considering* ε (or *CMS*-ε).

POTENTIAL RECORD-SELECTION STRATEGIES

To test the effect of a ground motion set's M, R and ε values, several selection methods are considered, and the resulting structural response outputs compared. One would ideally match the target distribution of all of these parameters simultaneously, but this is difficult in practice due to the finite number of recorded ground motions. Because of this limitation, the most important parameters should be identified and priority be given to matching them when selecting ground motions. Alternatively, one could select records based only on their spectral shape and not based on M, R or ε. With this in mind, four record-selection methods are considered, in order to investigate the effect of these different record-selection strategies on resulting estimated structural responses:

1. Select records at random from a record library, without attempting to match any specific record properties (this will be abbreviated as the *AR method*, as it uses arbitrary records).
2. Select records with magnitude (M) and distance (R) values representative of the site hazard, without attempting to match the ε values (this will be abbreviated as the *MR-BR method*, as it uses M, R-based records).
3. Select records with ε values representative of the site hazard, without attempting to match the magnitude and distance values (this will be abbreviated as the *ε-BR method*, as it uses ε-based records).
4. Select records with spectral shapes that match the conditional mean spectral shape given $\overline{M}$, $\overline{R}$ and $\overline{\varepsilon}$ as discussed earlier, but make no direct attempt to match the M, R or ε values (this will be abbreviated as the *CMS-ε method*, as it uses the conditional mean spectrum, considering ε).

With all four methods, only ground motions recorded at firm soil sites are considered, in order to match the conditions present at the example site of interest. Method 1 can be considered as a base case, where information about the causal events is ignored when selecting records (i.e. 40 records at random were selected from the library of 382). Method 2 reflects state-of-the-art procedures for probabilistic structural assessments [16, 17]. For Method 2, records were selected to have a minimum difference in magnitude and distance relative to the $\overline{M}$, $\overline{R}$ obtained from disaggregation (where a difference of one unit in magnitude was treated as equivalent to a difference of 40 km in distance). Method 3 is used to test the effect of ε. With this method, the 40 records with ε values closest to $\overline{\varepsilon}$ were selected. Later, a vector-valued IM will be used to account for magnitude, distance and ε simultaneously.

Finally, Method 4 is used to investigate the hypothesis that M, R and ε are proxies for spectral shape, and that spectral shape is the factor directly influencing structural response. If this is true, then records with a spectral shape matching the CMS-ε for a given M, R and ε will be accurate predictors of structural response, regardless of their actual M,R and ε values. With this method, records were selected that had a minimum sum of squared differences between their spectrum and the CMS-ε at seven periods ($0.16, 0.3, 0.5, 1.2, 1.5, 1.9$, and 2.4 s), after scaling the records to match the target $Sa(0.8\,\mathrm{s})$. The periods were selected to include shorter periods corresponding to higher modes of oscillation of the structure, and longer periods affecting non-linear response. The suggestion of ASCE 7-02 [18] to use $0.2T_1$ and $1.5T_1$ as the period range of interest was considered, although periods as large as $3T_1$ were also included because the structure will be driven to high levels of non-linearity which may cause significant effective-period lengthening.

The records selected using Methods 2–4 will depend (to differing degrees) on the site of interest, because causal M, R and ε values depend on the surrounding faults and their rates of activity. The records selected will also depend upon the hazard level of interest, because small frequent levels of ground motion typically have different associated magnitudes and distances than large rare levels of ground motions, but most importantly, ε changes radically as the ground motion level increases. This was seen in the changing conditional mean spectral shapes (and associated M, R and ε values) at three hazard levels in Figure 3 for a site in Van Nuys, California. Thus, if one is analysing the structure at multiple ground motion intensities, as will be done here, then the records should be re-selected at each level to reflect the changing sources.

Table I. Mean magnitude, distance and ε values from disaggregation of the Van Nuys site, and the corresponding mean values of the records selected using each of the four proposed methods. The mean magnitude, distance and ε values of the record library are 6.7, 33 km, and 0.2, respectively.

$Sa(0.8\,s)$ (g)	Target from disagg	1. AR method	2. MR-BR method	3. ε-BR method	4. CMS-ε method
Magnitude					
0.1	6.3	6.7	6.5	6.8	6.6
0.8	6.4	6.7	6.4	6.7	6.9
1.6	6.4	6.7	6.5	6.6	6.9
2.4	6.5	6.7	6.5	6.6	6.8
Distance (km)					
0.1	57.6	35.5	52.4	36.8	33.1
0.8	18.1	35.5	20.8	35.2	33.5
1.6	11.5	35.5	10.3	48.9	36.6
2.4	9.7	35.5	7.7	49.7	37.0
Epsilon (ε)					
0.1	0.0	0.0	0.6	0.0	0.1
0.8	1.5	0.0	0.0	1.4	0.5
1.6	2.1	0.0	−0.5	1.9	1.0
2.4	2.4	0.0	−0.5	2.0	1.2

The same set of records is used at all $Sa(0.8\,s)$ levels with Method 1. For Methods 2–4, records are re-selected at several levels of ground motion intensity according the disaggregation results at each level. The selected records used are listed in Reference [2, Appendix A]. For all four methods, 40 records were selected at 12 $Sa(T_1)$ levels between 0.1 and 4.0g. Note that if the target M, R and ε values were all matched simultaneously, then the records would already have the approximately the correct $Sa(0.8\,s)$ value. Because it is difficult to match all properties, however, it is necessary to employ some degree of record scaling to match the target $Sa(0.8\,s)$ values. Only scaling of accelerograms is employed; the frequency content of the records is not modified.

In Table I, the mean magnitude, distance and ε values of the selected records are given at four of the $Sa(T_1)$ levels, along with the target values obtained from disaggregation. A few observations can be made. When the record property is being matched explicitly, the selected records tend to match the target value, and otherwise the records tend to match the mean value of the record library. This is most apparent for the distance values, where the distance-matched (MR-BR) records closely match the target distances, but the other record sets have mean distance values of approximately 33 km: the mean of the record library. An interesting phenomenon arises with the records selected based on spectral shape. The magnitudes and distances of the selected records do not change appreciably as the Sa level varies, but the ε values do change in a manner similar to that of the target ε. This suggests that in order to match the spectral shape associated with a given M, R and ε, it is possible to substitute records with differing magnitudes and distances, but the spectral shapes associated with large ground motion levels tend to have positive ε values. The mean ε value of the CMS-ε records is lower than the target ε, however, implying that it is not entirely necessary to rely on only the largest (and rarest) ε records for selection of these more peaked conditional mean spectra.

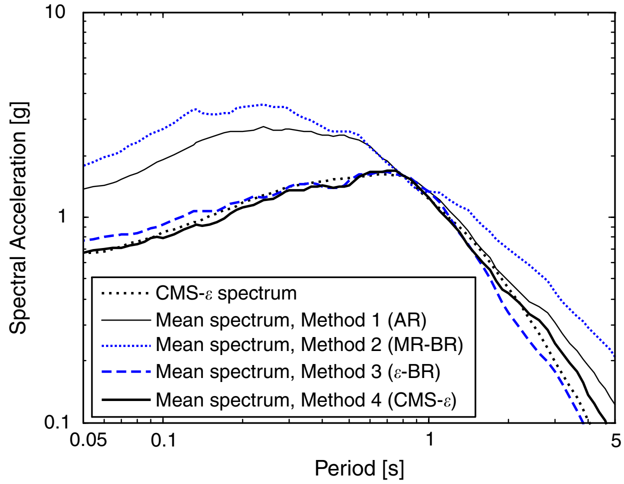


Figure 4. The CMS-ε at $Sa(0.8\,\mathrm{s}) = 1.6g$ (given $\overline{M} = 6.4$, $\overline{R} = 11.5\,\mathrm{km}$ and $\bar{\varepsilon} = 2.1$) and the mean response spectra of record sets selected using each of the four proposed methods.

In Figure 4, the mean response spectra of the selected record sets are compared to the target mean from Equation (1) at a given Sa level. At $Sa(0.8\,\mathrm{s}) = 1.6g$, the ε-BR and CMS-ε records have mean spectra close to the target, while the AR records have larger Sa values at some periods, and the MR-BR records have particularly high Sa values at nearly all periods other than 0.8 s.

STRUCTURAL ANALYSIS

The records selected in the previous section were used as inputs for non-linear dynamic analysis of a structure, to investigate any differences in resulting structural responses. The structure is a seven-storey reinforced concrete frame building studied as part of a larger performance-based engineering project [19]. The building is located in Van Nuys, California, at the same site for which the ground motion hazard analysis above was conducted. A 2D model of the transverse frame created by Jalayer [20] is used here. This model has an elastic first-mode period of 0.8 s (which is the reason why $Sa(0.8\,\mathrm{s})$ has been used as the IM in this study) and uses non-linear elements with strength and stiffness degradation in both shear and bending [21]. The maximum observed interstorey drift ratio was used as the structural response parameter of interest. For simplicity, only results from this single structure are presented here; the record-selection procedures have been repeated for two additional structures and similar results were observed [2, Appendix F].

A variety of summary statistics can be used to compare the responses caused by each set of records. The geometric mean of maximum interstorey drift ratio as a function of IM is shown in Figure 5(a), using the results from the four record-selection methods. The ε-based records produce the lowest geometric mean responses, with the CMS-ε records producing approximately the same response. The other two methods produce slightly larger mean

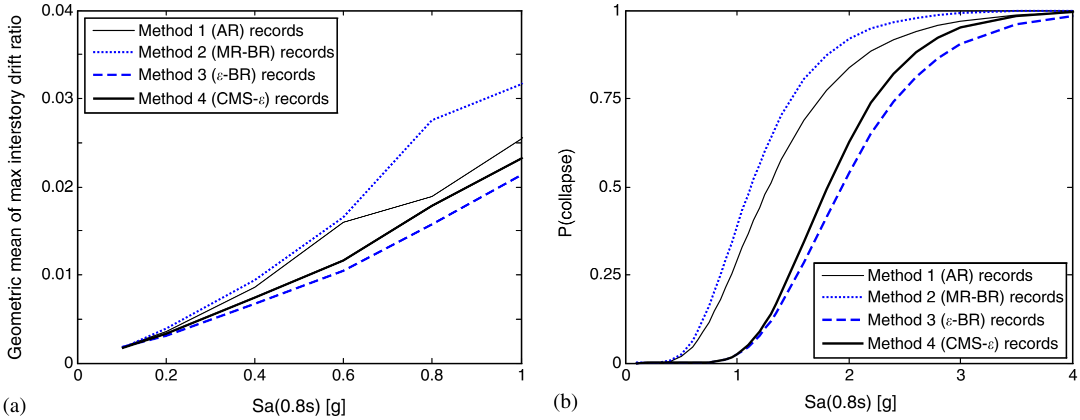


Figure 5. (a) The geometric mean of maximum interstorey drift ratio for records that do not cause collapse, plotted vs $Sa(T_1)$ for the four record-selection methods considered; and (b) probability of collapse vs $Sa(T_1)$ (i.e. the collapse 'fragility curve') using the four record-selection methods considered.

responses. This comparison is of particular relevance to current practice, where the objective is to estimate the mean response at a specified ground motion intensity level [7]. The x axis of this plot is limited to Sa values less than $1g$, because at larger Sa levels, a significant portion of records causes collapse, and thus comparisons of non-collapse responses are less meaningful. The standard deviations of log maximum interstorey drift ratio were also computed. The ε-based records produce slightly smaller dispersions than the arbitrary records and M, R-based records, and the CMS-ε records produce significantly lower dispersions, because by selecting records based on their similarity to a mean spectrum, records with 'smooth' spectra were preferentially selected. As long as these smoother spectra do not bias response, this smaller dispersion implies that mean responses can be estimated more efficiently (i.e. with fewer records). The dispersion is artificially lower than would be observed if all records were considered, however. This is not a concern if only the mean response is of interest, but it may affect the results of probabilistic 'drift hazard' reliability assessments. The reduced dispersion does not appear to affect the drift hazard curve computed below, but further investigation is needed to determine whether this is true in general.

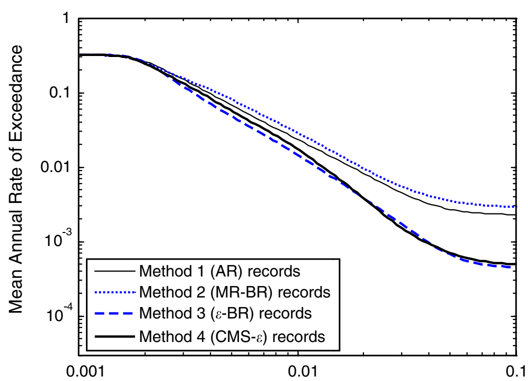
In addition, the probability of collapse versus Sa (i.e. the collapse fragility curve) was computed for the four record-selection methods by counting the fraction of records that cause collapse at each Sa level and fitting a lognormal distribution to the results using the maximum likelihood method [2, Appendix D]. The result is seen in Figure 5(b). The arbitrary records and M, R-based records have larger probabilities of collapse, particularly in the left tail of the distribution, which tends to be most important (because smaller Sa values occur much more frequently than the larger Sa values at the right end of the distribution). The estimated probabilities of collapse versus Sa from the CMS-ε records and the ε-based records are nearly identical.

The method used to select records has a significant effect on the resulting estimates of structural response, as seen in the non-collapse geometric means and the probability of collapse estimates. It is noted that the ε-BR and CMS-ε methods produce similar geometric mean responses and collapse probabilities, with the latter method giving lower dispersions.

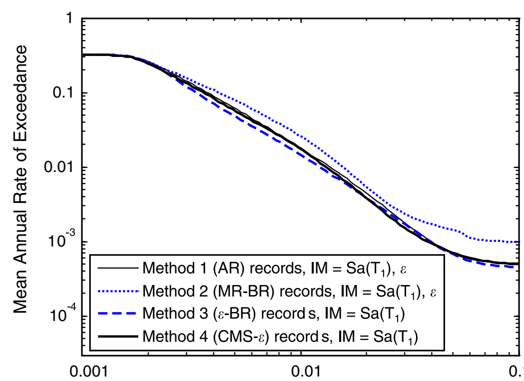
Incorporating ground motion hazard to compute drift hazard

An additional way to compare results from the various record-selection methods is to combine the estimated distributions of response as a function of $Sa(T_1)$ with the probability of exceedance of each $Sa(T_1)$ level, to compute the mean annual frequency of exceeding a given structural response level (sometimes referred to as a drift hazard curve). The mathematical details of this simple integration are explained in detail in, e.g. Reference [3]. These computations incorporate both the collapse and non-collapse responses discussed in the previous section. The resulting drift hazard curves are shown in Figure 6(a). The AR method and MR-BR method records produce higher estimated probabilities of exceedance than the other two methods, particularly at large response levels. Further, the results from the CMS-ε and ε-BR methods are nearly identical. This is consistent with earlier findings regarding the effect of ε, [3], but here the effect is seen using careful record selection rather than a vector-valued measure of ground motion intensity.

We can further verify that variation among the results in Figure 6(a) is due to variation in spectral shape (as accounted for by either ε or the CMS-ε) by incorporating a vector-valued IM consisting of $Sa(T_1)$ and ε, using the method of Reference [3]. A vector IM can mimic the effect of careful record selection, as is explained in detail elsewhere [1]. This is seen in Figure 6(b)—when the vector IM is used to compute drift hazard curves, the results are in much closer agreement. The curve from the MR-BR method records does not agree perfectly with the others, but the agreement is better than in Figure 6(a) before the effect of ε was accounted for. The remaining difference is likely due to random variation among ground motions, and not a systematic effect of any of considered ground motion parameters. The structural response results of Figure 5 can also be modified using a vector IM including ε, and here the ε parameter also causes these results to agree more closely.



(a)



(b)

Figure 6. Mean annual frequency of exceeding various levels of maximum interstorey drift ratio, as computed using: (a) the scalar intensity measure $Sa(T_1)$; and (b) the vector intensity measure $Sa(T_1)$ and ε.

Vector-valued IMs can also be used to incorporate the effect of magnitude or distance with the ε-based records. Incorporating magnitude or distance in the IM, however, did not result in appreciable changes to the drift hazard curve (consistent with the findings in Reference [3]). These results indicate that the structural response estimates obtained from the AR method and MR-BR method records are biased, because incorporation of additional information regarding ε results in a change to the geometric mean response and probability of collapse estimates. Conversely, response estimates obtained from the CMS-ε method and ε-BR method records do not appear to be biased, as the incorporation of additional information regarding the ground motions does not result in a change to the response estimates. This suggests that ε (or its implied effect on mean spectral shape) should be given primary consideration when selecting records, with lesser consideration given to magnitude or distance.

CONDITIONAL MEAN SPECTRA VERSUS UNIFORM HAZARD SPECTRA

The target spectrum used most frequently today for analysis of buildings is the UHS [18, 22, 23]. A UHS is defined as the locus of points such that the spectral acceleration value at each period has an exceedance probability equal to the specified target probability. PSHA analyses are performed independently for each period when computing this spectrum, so it is important to remember that nothing can be said about the joint occurrence or exceedance of all of these spectral values simultaneously. Thus, treating the UHS as the spectrum of a single earthquake event is questionable, as has been noted by others [24–26]. Because of this concern, nuclear industry design procedures provide an alternative procedure for defining a design spectrum [4–6]. The difference between the nuclear and building design procedures indicates that a consensus has not yet emerged regarding appropriate design spectra.

The reason why a UHS does not represent a spectrum caused by a single earthquake at a given site is typically explained as follows: the high-frequency portion of the UHS is often dominated by small nearby earthquakes, while the low-frequency portion is dominated by larger, more distant earthquakes. Because the high- and low-frequency portions come from different events, no single earthquake will produce a response spectrum as high as the UHS throughout the frequency range considered. While it is true that no single earthquake is likely to produce a spectrum as high as the UHS, an additional underappreciated reason for this is the variability in spectral values (for a given magnitude and distance). At each period, the spectral acceleration value given a magnitude and distance is random—it could be higher or lower than the mean prediction. For low annual probability (long-return-period) design criteria, the *UHS is almost always higher than the mean spectrum* (*or spectra*) *for the dominant event* (*or events*) *at a site* (i.e. ε is greater than 0, as explained in Reference [3]). Even when a record has a spectral acceleration value as large as the UHS at a given period, it is unlikely to be as high as the uniform hazard spectra at all periods. Thus, a spectrum that is equal to the UHS at a range of periods has a much lower probability of exceedance than the probability level assigned to the UHS. Therefore, using a UHS as a target spectrum for probabilistic analysis would be conservative, due to variations in causal magnitudes, distances *and epsilons* from period to period.

The fact that a UHS is always higher than individual CMS-ε, as can be seen in Figure 7(b), suggests that a UHS may be a reasonable target spectrum in some circumstances. Computation of the CMS-ε requires knowledge of T_1, so if one is performing expensive analyses

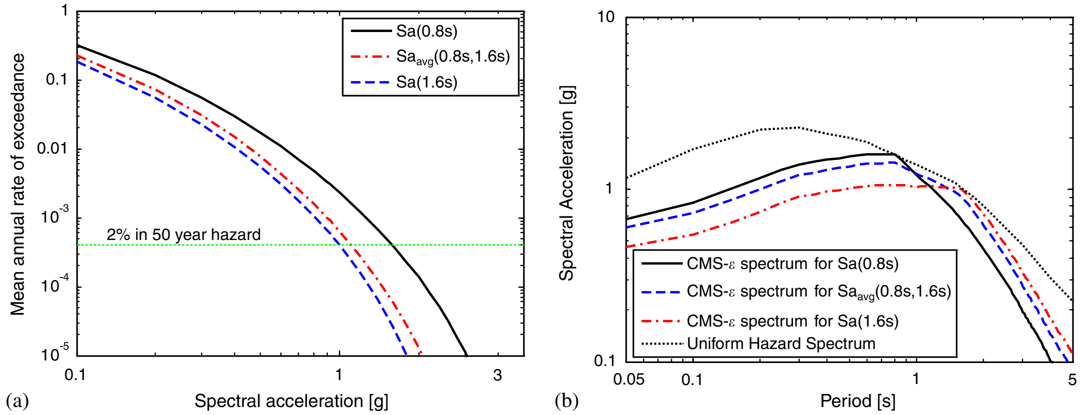


Figure 7. (a) Hazard curves for $\ln Sa(0.8\,\mathrm{s})$, $\ln Sa(1.6\,\mathrm{s})$, and $\ln Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$ at the Van Nuys site; and (b) CMS-ε for these three IMs at the 2% in 50 year hazard level, and the 2% in 50 year uniform hazard spectrum.

or experiments on a system with an unknown period or many sensitive periods *and* cannot run many tests, the UHS could instead be used as a target spectrum, recognizing that the results may be quite conservative. But if one can afford to perform many analyses, a less conservative estimate of responses can be obtained by using CMS-ε conditioned on target *Sa* values at several periods, and taking the envelope (or some other combination) of responses estimated with records based on these spectra. That is, rather than estimating the response from an envelope of spectral values (the UHS), one could estimate the envelope of responses from several CMS-ε. This should be less conservative than using the UHS, and more suited for use in probabilistic assessments. An alternative approach would be to adopt an IM that averages a record's response spectrum across a range of periods; this avoids the need to use spectra that are peaked at specific periods, as will be discussed in the following section.

DO WE REALLY WANT RECORDS WITH A PEAK IN THEIR SPECTRUM? CONSIDERATION OF SPECTRAL ACCELERATION AVERAGED OVER A PERIOD RANGE

It is assumed above that earthquake intensity is measured by $Sa(T)$—that is, spectral acceleration at a single period. This IM is a perfect predictor of structural response for elastic single-degree-of-freedom systems with natural period T. For multiple-degree-of-freedom structures, $Sa(T)$ can effectively predict even non-linear structural response when the period T is chosen to equal the first-mode period of the structure, especially if the structure is 'first-mode dominated' [27]. For these reasons it is often used in probabilistic seismic reliability assessments.

It was seen above that extreme (rare) values of $Sa(T_1)$ are not associated with equally extreme *Sa* values at all periods, due to a lack of perfect correlation among response *Sa* values at differing periods. This phenomenon results in the spectrum of rare ground motions (as defined by their $Sa(T_1)$ level) having a peak at $Sa(T_1)$, as was seen earlier. But if the structural response parameter of interest is sensitive to Sa values at multiple periods, then perhaps this specific peaked spectrum should not be of primary concern (loosely speaking, rather than worrying about a spectrum that is 'very' strong at a single period, one might worry more about an equally rare spectrum that is 'somewhat' strong at several periods). In this case an IM which averages spectral acceleration values over a range of periods might be a better indicator of structural response [1, 28]. The relationship between this IM and target response spectra will now be shown.

Consider the geometric mean of spectral acceleration values at a set of periods:

$$Sa_{\text{avg}}(T_1, \ldots, T_n) = \left(\prod_{i=1}^{n} Sa(T_i) \right)^{1/n} \tag{3}$$

where $T_1, \ldots, T_n$ are the n periods of interest. The computations here are general for any set of periods, and so in this section T_1 need not refer to the first-mode period of the structure. This can also be expressed as a (arithmetic) mean of logarithmic spectral acceleration values

$$\ln Sa_{\text{avg}}(T_1, \ldots, T_n) = \frac{1}{n} \sum_{i=1}^{n} \ln Sa(T_i) \tag{4}$$

This formulation is convenient, because ground motion prediction equations can be easily developed for an $\ln Sa_{\text{avg}}$ with an arbitrary set of periods, $T_1, \ldots, T_n$, using existing models. The mean and variance of $\ln Sa_{\text{avg}}(T_1, \ldots, T_n)$ are given by

$$E[\ln Sa_{\text{avg}}(T_1, \ldots, T_n)] = \frac{1}{n} \sum_{i=1}^{n} E[\ln Sa(T_i)] \tag{5}$$

$$\text{Var}[\ln Sa_{\text{avg}}(T_1, \ldots, T_n)] = \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \rho_{\ln Sa(T_i), \ln Sa(T_j)} \sigma_{\ln Sa(T_i)} \sigma_{\ln Sa(T_j)} \tag{6}$$

where $E[\ln Sa(T_i)]$ and $\sigma_{\ln Sa(T_i)}$ are the conditional mean and standard deviation of $\ln Sa(T_i)$, available from popular ground motion prediction models (e.g. Reference [11]). The term $\rho_{\ln Sa(T_i), \ln Sa(T_j)}$ was given in Equation (2) above. Note that Equations (5) and (6) are the conditional logarithmic mean and variance given magnitude, distance, etc., as with standard ground motion prediction models for $\ln Sa(T)$. Further, if $\ln Sa(T_i)$ values are assumed to be jointly Gaussian, as is often done [29, 30], then their sum is also Gaussian and Equations (5) and (6) completely define the distribution of $\ln Sa_{\text{avg}}(T_1, \ldots, T_n)$. Probabilistic seismic hazard analysis and disaggregation can then be performed using this IM, exactly as is done for any single spectral acceleration value.

The CMS-ε can also be computed for this IM. To complete the calculation, the correlation coefficient between any $\ln Sa(T)$ and $\ln Sa_{\text{avg}}(T_1, \ldots, T_n)$ is needed. This correlation coefficient can be shown to equal

$$\rho_{\ln Sa(T), \ln Sa_{\text{avg}}(T_1, \ldots, T_n)} = \frac{\sum_{i=1}^{n} \rho_{\ln Sa(T), \ln Sa(T_i)} \sigma_{\ln Sa(T_i)}}{\sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} \rho_{\ln Sa(T_i), \ln Sa(T_j)} \sigma_{\ln Sa(T_i)} \sigma_{\ln Sa(T_j)}}} \tag{7}$$

The procedure used earlier can now be repeated for $\ln Sa_{\text{avg}}(T_1, \ldots, T_n)$.

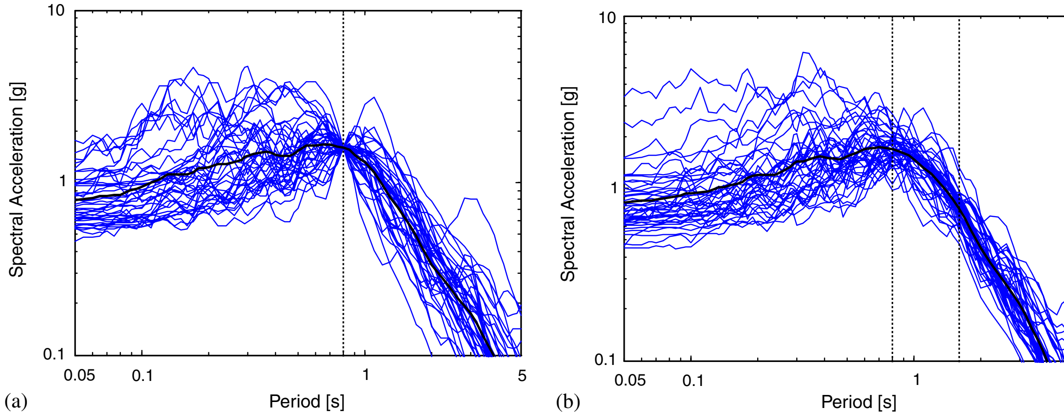


Figure 8. Records scaled to target IM levels associated with 2% in 50 year probability of exceedance. Records were selected using the ε-BR method, where the ε values came from the appropriate PSHA disaggregation: (a) records scaled to $\ln Sa(0.8\,\mathrm{s})$; and (b) records scaled to $\ln Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$.

For illustration, consider a simple case of Equation (4) consisting of periods at only T_1 (the first-mode period of the considered structure) and $2T_1$. This is, in fact, equivalent to the IM considered by Cordova *et al.* [31]. We will again consider a T_1 value of 0.8 s, so that $2T_1 = 1.6\,\mathrm{s}$. Using the Abrahamson and Silva [11] ground motion prediction model for $\ln Sa(0.8\,\mathrm{s})$ and $\ln Sa(1.6\,\mathrm{s})$ and the prediction for $\ln Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$ based on the above equations, three hazard analyses were performed for the Van Nuys site described above (a procedure also performed in Reference [31]). Their hazard curves are shown in Figure 7(a). At the 2% in 50 year hazard level, the CMS-ε is computed and displayed in Figure 7(b) for each of the three IMs using their respective IM values and associated disaggregations on M, R and ε. Note that with the $\ln Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$ CMS-ε, the peaks at individual periods are lessened, but this smoother spectrum is different than the UHS (it will always be lower than the UHS).

Further intuition regarding the spectra associated with this IM can be obtained from Figure 8, where records are selected and scaled to target IM levels using either $Sa(0.8\,\mathrm{s})$ or $Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$. Records were selected using the ε-BR method, with the ε values obtained from the PSHA analyses displayed in Figure 7(a). It should be emphasized that although the spectra in Figure 8(b) appear to be casually scaled using a conventional method to minimize the RMS error between the record spectra and a target spectrum over a range of periods (e.g. Reference [18]), they have actually been scaled precisely so that each record has a common specified value of $Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$. Therefore, they can be used unambiguously to obtain a drift hazard curve as was done earlier with $Sa(0.8\,\mathrm{s})$.

The mean spectra from Figure 8(a) and (b) have different shapes, and the shapes are nearly identical to the mean shapes predicted in Figure 7(b); thus, the $Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$ IM produces selected records that tend to be less peaked. Also, the spectra in Figure 8(a) clearly display the characteristic 'pinch' at 0.8 s, while the spectra in Figure 8(b) are never equal at any period. The spectra in Figure 8(b), however, have less variation in the range of 1–2 s than the records in Figure 8(a). This suggests that by giving up perfect knowledge of Sa at 0.8 s, the $Sa_{\mathrm{avg}}(0.8\,\mathrm{s}, 1.6\,\mathrm{s})$ IM is able to provide improved information about Sa values at a range of periods. The 'information' provided at each period by these two IMs at various periods can be more rigorously defined using the conditional variance of the response spectrum given a value of the IM level; this idea is developed in more detail elsewhere [2].

If a structure is sensitive to a range of periods, the possibility exists that the IM $\ln Sa_{avg}(T_1,\ldots,T_n)$ could be designed specifically to incorporate these periods. The Sa values at each period could even have differing weights to reflect to some degree the relative importance of each to structural response [1, 31, 32]. Structural response conditional on this IM may be less sensitive to remaining spectral shape variation, so that the record-selection scheme used would no longer affect the estimated response. If this IM were to be adopted, extra effort would be required to choose the periods appropriately and to perform ground motion hazard analysis for the new IM. The effectiveness of this IM, relative to $Sa(T_1)$, will depend upon the level of non-linearity in the structure and whether it is sensitive to higher-mode responses. It will also depend upon the structural response parameter of interest. An investigation into its effectiveness has been performed for a single structure [31], but more work is needed to draw general conclusions. If it does prove helpful, however, the concept of CMS-ε can be used for this IM as well. The resulting CMS-ε are not as 'peaked' as CMS-ε based on spectral acceleration at a single period, but they still differ from uniform hazard spectra.

CONCLUSIONS

Selection of earthquake ground motions for dynamic analysis of structures has been investigated, with the aim of accurately measuring the distribution of structural response associated with earthquake ground motions of a specified intensity, as measured by $Sa(T_1)$. In order to identify ground motion properties that affect the response of a non-linear multi-degree-of-freedom structure, records were selected using several methods: (1) use arbitrary records, (2) select records to match causal magnitudes and distances, or (3) select records to match causal ε values. Causal values of magnitude, distance and ε depend upon the site of interest and the ground motion intensity level of interest, and can be determined from probabilistic seismic hazard disaggregation. A method for calculating the expected spectral shape given a specified $Sa(T_1)$ level and its associated causal magnitude, distance and ε values was presented and termed the conditional mean spectrum considering ε (CMS-ε). This CMS-ε is similar to spectra used for design of nuclear facilities, except that the effect of ε is not considered in those spectra. As a fourth record-selection alternative, records were selected to match this CMS-ε, regardless of the records' magnitude, distance and ε values.

The response spectra of records selected using these four methods were examined; it was seen that the CMS-ε at a rare, extreme ground motion intensity, as measured by $Sa(T_1)$, has a 'peak' at T_1. Records selected based on their ε values or their match with the CMS-ε tend to have this peak in their spectra, unlike records selected using the other two methods. For each of the record-selection methods, median structural response and probability of collapse were computed at a range of ground motion intensity levels, and the drift hazard curve was computed. For the records selected arbitrarily or based on magnitude and distance, inclusion of the parameter ε in a vector IM resulted in reduced estimates of structural response relative to the estimates obtained with the scalar IM $Sa(T_1)$; this indicates that response estimates obtained using these record-selection approaches are biased when $Sa(T_1)$ is used as the IM.

Conversely, response estimates obtained from ε-based records or CMS-ε records were not sensitive to the inclusion of other parameters in a vector IM, suggesting that these records produce unbiased results. Other work with these ground motion sets suggests that the records selected based on ε or CMS-ε can also be scaled without producing biased responses, unlike the arbitrary records or M, R-based records [2]. These observations can be explained by the idea that spectral shape (i.e. spectral acceleration values at other periods, given Sa at T_1) is the record property that directly affects structural response, whereas magnitude, distance and ε are merely proxies for spectral shape (and ε appears to be a particularly important proxy).

The records selected based on CMS-ε produced smaller dispersions in structural response than records obtained with the other procedures, because records with smooth response spectra were preferentially selected. This reduces the number of records needed to obtain mean response estimates with a given confidence level. The dispersion is somewhat artificially suppressed, however, because it is obtained by ignoring records with rough spectra (which are also expected to occur in reality). This may be problematic for probabilistic drift hazard assessments, where accurate estimates of both the mean and dispersion of response are needed, although no significant errors were observed in the assessments performed here. Future work will focus on exploiting the benefit of this reduced dispersion while also ensuring that it does not introduce errors in the analysis.

Response spectra of ground motions whose intensity is defined based on spectral acceleration averaged over a range of periods were considered. It was seen that the mean spectra of motions defined in this way do not have the 'peak' seen when $Sa(T_1)$ is used as the intensity measure (IM). This definition of intensity provides improved but limited information about spectral values at a defined set of periods, at the cost of giving up perfect information about spectral acceleration at T_1. Probabilistic seismic hazard analysis, record-selection criteria and target spectra can all be obtained for this IM in the same way as for the standard $Sa(T_1)$ IM. The question of when this IM is more efficient than $Sa(T_1)$ was not considered.

Based on the findings in this paper, the following suggestions for record selection can be made: the record property ε at the period T_1 is an important property to match when selecting ground motions for analysis, where the ground motion intensity is measured using $Sa(T_1)$. This applies for estimation of mean response at a given $Sa(T_1)$, as well as for fully probabilistic drift hazard assessment. If an analyst also prefers to match target magnitude and distance values when selecting ground motions, care should be taken to ensure that this objective does not inhibit the selection of records with appropriate ε values. Although not investigated here, it is likely also important to match soil type due to its effect on spectral shape, especially at soft soil sites [16] (records from stiff soil sites were used exclusively in this study, to match the soil conditions at the example site of interest). As an alternative to selecting earthquake records based on magnitude, distance and/or ε, one can instead use the procedure outlined above to determine the CMS-ε for the $Sa(T_1)$ level of interest. Records can then be selected to match this spectrum without worrying further about magnitude, distance or ε. This spectral-shape-matching approach is appealing not only because it is seen to avoid response prediction bias, but also because there are by definition few records with ε values equal to the ε values of rare intense ground motions of engineering interest. The relatively greater number of records with a spectral shape matching the shape of rare ground motions means that there are potentially a larger number of appropriate ground motions available with this approach.

The procedure considered here requires knowledge of the structure's location (for ground motion hazard analysis) and a structural model (for dynamic analysis and determination of the structure's first-mode period). Implications for simplified design guidelines, where less is known about the structure, were not considered in detail. The conclusions herein are supported by empirical observations of maximum interstorey drift ratios in three example frame structures of varying periods subjected to large numbers of ground motions. Based on the ideas developed in this paper, it is expected that these conclusions will apply for other types of structures and other response parameters, but further studies will be helpful in confirming this.

ACKNOWLEDGEMENTS

This work was supported primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation, under Award Number EEC-9701568 through the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

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