8th Pacific Conference on Earthquake Engineering

December 5-7, 2007

Measuring Bias in Structural Response Caused by Ground Motion Scaling

Jack W. Baker

Stanford University, USA

ABSTRACT:

The selection and scaling of earthquake ground motions is an important step in defining the seismic loads that will be applied to a structure during structural analysis, and serves as the interface between seismology and engineering. Recent research suggests that potential problems caused by ground motion scaling are due primarily to discrepancies in the shape of elastic response spectra between the ground motion to be scaled and the 'target' ground motion desired. These discrepancies may result in the scaled ground motions causing different levels of structural response than the response that would be caused by (unscaled) ground motions naturally at the intensity level of interest. A method for detecting such scaling bias is proposed, based on selecting a suite of ground motion records that have been scaled to all have the same intensity level (where here intensity is measured by spectral acceleration at the structure's first-mode period). The structural responses associated with the records are plotted versus the records' scale factors. Trends between the two values quantify the extent to which record scaling is causing biased structural response. Example results obtained using this method suggest that records selected based on the ground motion parameter ε (or that otherwise account for the spectral shape implied by ε) can be safely scaled without introducing any bias, whereas the records selected using other methods have biased structural responses when scaled.

1 INTRODUCTION

An important consideration at the interface between seismology and earthquake engineering is the selection and processing of earthquake ground motions for use in performing dynamic structural analysis. It is common in practice to select recorded ground motions and 'scale' them by increasing their amplitude to match a desired earthquake intensity level. Due to limitations in recorded ground motion libraries, scaling will continue to be used for the foreseeable future to represent extreme ground motions. But questions remain regarding how the ground motions should be selected, and whether the scaled ground motions are truly representative of ground motions with the given intensity level (where intensity is measured using a parameter such as spectral acceleration at the first mode period of the structure). From an engineer's perspective, the question can be phrased, 'will ground motions scaled to a specified intensity produce the same structural responses as unscaled ground motions naturally at that intensity level?'

Early quantitative investigations into ground motion scaling indicated that a suite of ground motions may be safely scaled to the suite's median spectral acceleration value, at a period T, without biasing the median response of a structure having the same first-mode period T (Shome et al. 1998, Iervolino and Cornell 2005). But recent work suggests that in some other situations record scaling may induce some bias in structural response (Baker and Cornell 2005b, Luco and Bazzurro 2005). This bias appears to result from the scaled ground motions having inappropriate values of spectral shape or the parameter ε, which is an indirect measure of spectral shape (Baker and Cornell 2005a). This conclusion fits with some intuitive concerns about record scaling: namely, that low intensity ground motions have different frequency content than rare or extreme ground motions. Han and Wen (1994), for example, speculated that "scaling an earthquake to attain a target damage level of different intensity is questionable since scaling a ground motion does not account for variations in ground motion characteristics (e.g., frequency content) which change with intensity."

An important feature of these ground motion scaling studies is that record selection and scaling approaches are evaluated by studying the response of structures subjected to these motions. If it can be verified that scaled ground motions produce structural responses similar to those from unscaled ground motions having the same intensity, then it can be concluded that the given scaling approach is valid. This pragmatic viewpoint has also been taken in a recent paper studying record scaling for geotechnical analysis (Watson-Lamprey and Abrahamson 2006).

2 RECORD SELECTION

There are a variety of methods for selecting the suite of ground motions to be used for analysis, and the selection method may have an effect on the bias resulting from scaling the ground motions. Four methods of record selection will be considered below. Two of these methods involve the ground motion parameter ε ('epsilon') so its importance will be summarized briefly, followed by a description of the four record selection methods considered.

2.1 *The ground motion parameter ε, and a predictive model for spectral shape*

A common finding of record selection research is that structural responses are dependent upon spectral shape, and that if scaled ground motions have the same spectral shape as the target ground motions, the resulting structural responses from scaled ground motions are statistically similar to responses from unscaled ground motions. Magnitude and distance can affect the spectral shape of records, and the ground motion parameter ε has also been seen to be a useful predictor of spectral shape (Baker and Cornell 2005a, 2006b). The parameter ε is defined as the number of standard deviations between the observed spectral value and the median prediction from an attenuation function. Records with large positive ε values at a given period are typically associated with a peak in the response spectrum at that period, because the ε value indicates an extreme/rare spectral value at that period while other spectral values at other periods are not necessarily so extreme. This tendency of high-ε ground motions to have a peaked spectral shape will be an important consideration in the results below. Baker and Cornell concluded that the effect of ε is at least as great as that of magnitude or distance.

To utilize this finding, however, it is necessary to know the response spectrum associated with ground motions having the target ground motion intensity. The well-known Uniform Hazard Spectrum (UHS) is unappealing for this application, as it is an envelope of spectral values associated with multiple ground motions, rather than a description of a single ground motion. Problems with treating the UHS as the spectrum of a single ground motion have been noted by other researchers (Reiter 1990, Naeim and Lew 1995, Bommer et al. 2000).

A more suitable alternative for this problem is to find 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 (Baker and Cornell 2006b). To develop the target spectrum, we first specify the first-mode period of the structure of interest, T_1. The $Sa(T_1)$ value corresponding to a target probability of exceedance at the site is then obtained using PSHA and denoted $Sa(T_1)^*$. We then use deaggregation to find the mean of the magnitude, distance and ε values (denoted $\bar{M}$, $\bar{R}$ and $\bar{\varepsilon}$) that cause the occurrence of $Sa(T_1)^*$ level (e.g., McGuire 1995). $\bar{M}$ and $\bar{R}$, in turn, via ground motion prediction models, determine the means and standard deviations of the response spectral values for all periods, and $\bar{\varepsilon}$ 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 $\bar{\varepsilon}(T_1)$, we can calculate the conditional distribution of Sa values at other periods using only the deaggregation 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 from procedures to develop target spectra for analysis of nuclear facilities (DOE 1996, NRC 1997, ASCE 2005), except that those methods incorporate only the causal M and R values from disaggregation. The target spectra must then be scaled up to match the specified Sa value. Here, the effect of ε is incorporated as well, given the finding that ε is a useful predictor of structural response.

The mean target response spectrum based on $\bar{M}$, $\bar{R}$ and $\bar{\varepsilon}$ can be computed in the following manner

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

$$\sigma_{\ln Sa(T)|\ln Sa(T_1)=\ln Sa(T_1)^*} \approx \sigma_{\ln Sa}(\bar{M},T)\sqrt{1-\rho^2_{\ln Sa(T_1),\ln Sa(T)}} \tag{2}$$

where $\bar{M}$, $\bar{R}$ and $\bar{\varepsilon}(T_1)$ come from deaggregation given $Sa(T_1)=Sa(T_1)^*$. The terms $\mu_{\ln Sa}(\bar{M},\bar{R},T)$ and $\sigma_{\ln Sa}(\bar{M},Th)$ are the marginal mean and standard deviation of ln*Sa* at *T*, as predicted by a ground motion prediction ('attenuation') relationship. A model for the correlation term $\rho_{\ln Sa(T_1),\ln Sa(T)}$ is given by Baker and Cornell (2006a). Note that the substitution of mean values for magnitude, distance and ε, rather than the complete disaggregation distributions, is an approximation, but is believed to be accurate in most practical situations (Baker and Cornell 2005b, Appendix E). Examples of this target spectrum are shown in Figure 1a, conditioned on the *Sa*(0.8s) level exceeded in Los Angeles with probabilities of 50%, 10% and 2% in 50 years. The spectrum given by Equation 1 will be termed a 'Conditional Mean Spectrum, considering ε,' (CMS-ε) because it is a mean value, conditional on a target $Sa(T_1)$ value, and it considers ε, unlike similar spectra specified by nuclear facility guidelines.

This target spectrum differs from the more commonly used Uniform Hazard Spectrum (UHS) (McGuire 2004). A 10% in 50 years UHS is shown in Figure 1b, along with CMS-ε for three periods of interest. The UHS is presented here to illustrate the relative difference of the proposed conditional mean spectrum, but is not used in the results that follow. Several observations can be made from Figure 1: the CMS-ε is dependent upon the *Sa* value of interest (as seen in Figure 1a, where the spectrum becomes more peaked as $Sa(T_1)$ increases), as well as the period of interest (as seen in Figure 1b). The spectrum also depends upon the site of interest, which will affect the magnitudes and distances to the causal faults.

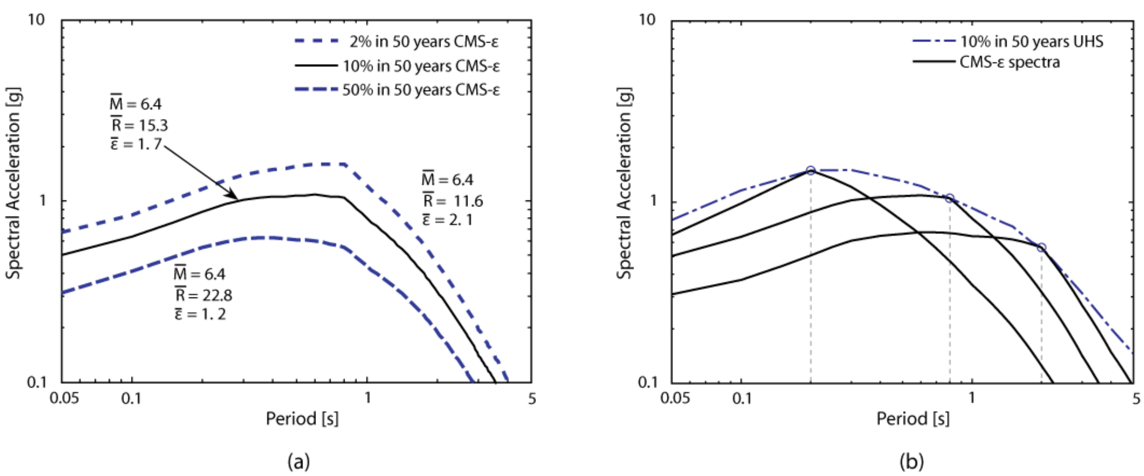

Figure 1: (a) Conditional mean spectra, considering ε, for a site in Los Angeles, given occurrence of *Sa*(0.8s) values exceeded with 2%, 10% and 50% probabilities in 50 years. (b) Uniform hazard spectrum corresponding to 10% probability of exceedance in 50 years, and conditional mean spectra associated with *Sa* values at T_1 = 0.2, 0.8 and 2 seconds.

2.2 *Record selection methods*

When choosing ground motions for estimation of structural response, ideally the distribution of magnitude, distance *and* ε values in the record set would equal the condition distribution of magnitude, distance and ε values seen at the site of interest, given $Sa(T_1)$ (as determined from PSHA disaggregation). Note that this conditional distribution will change as a function of the $Sa(T_1)$ level, so different records would need to be selected for different $Sa(T_1)$ levels. Matching all of these values simultaneously poses practical challenges when selecting from a finite set of recorded ground motions, so it would be helpful to understand which parameters have the greatest effect on the resulting structural response, so that greatest priority can be given to matching those parameters.

To test the relative effect of the M, R and ε values on structural response, four record-selection methods are now considered, and the resulting structural response outputs compared:

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 and distance 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 by Equation 1, but make no further attempt to directly match the target M, R or ε values. This will be abbreviated as the 'CMS-ε Method,' as it uses the Conditional Mean Spectrum, considering ε.

For each Sa level of interest, 40 ground motions were selected using each of the methods (the specific records selected are listed in Baker and Cornell 2005b). The response spectra of the records selected using Method 4 are shown in Figure 2a, and the mean of the spectra associated with each of the four methods are shown in Figure 2b. In this figure, the period of interest is 0.8 seconds and the target Sa(0.8s) value is 0.6g. The $\bar{M}$, $\bar{R}$ and $\bar{\varepsilon}$ associated with the example site and Sa(0.8s) value are 6.4, 18 km and 1.5, respectively. In Figure 2a, note that while the individual spectra follow the general shape of the target spectrum and exactly equal the target at 0.8 seconds (due to scaling), there is still variability in the spectra at other periods. In Figure 2b, note that the spectra associated with methods 3 and 4 have a peak at 0.8 seconds, while records selected using methods 1 and 2 do not.

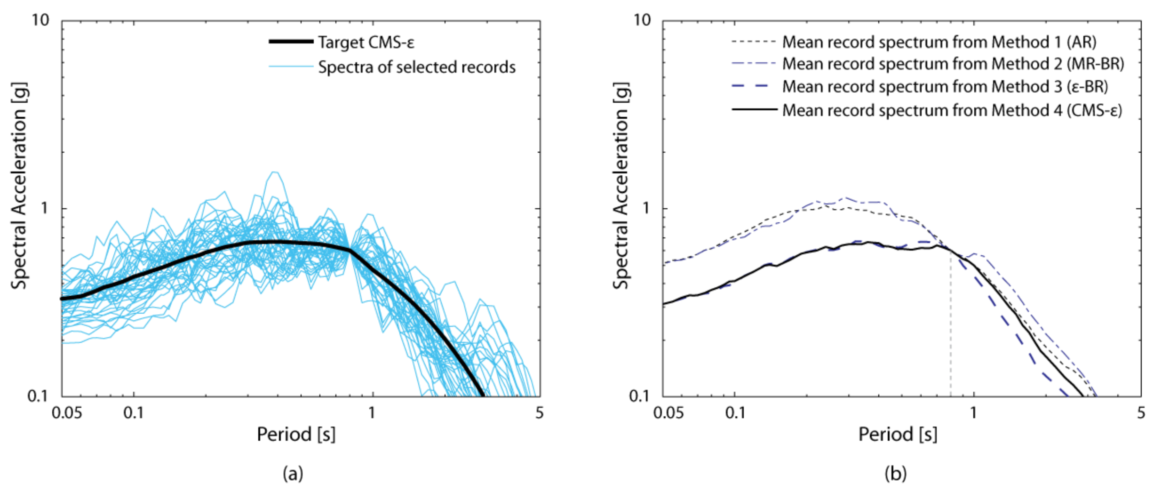

Figure 2: (a) Conditional Mean Spectrum at Sa(0.8s)=0.6g (given $\bar{M}$=6.4, $\bar{R}$=18 km and $\bar{\varepsilon}$=1.5) and the response spectra of records selected to match it (i.e., using Method 4). (b) The mean response spectra of record sets selected using each of the four proposed record selection methods, given Sa(0.8s)=0.6g.

3 STRUCTURAL MODEL

To demonstrate the proposed evaluation approach, an example analysis was performed using a seven-story reinforced concrete moment frame building. This structure, which was studied as part of a larger research effort (Krawinkler 2004) is located in the Los Angeles area, at the same site for which the ground motion hazard analysis above was conducted. A 2D model of the transverse frame created by Jalayer (2003) is used here. This model has an elastic first-mode period of 0.8 seconds (which is why *Sa* at 0.8s has been used in the above examples) and uses nonlinear elements with cyclic strength and stiffness degradation in both shear and bending (Pincheira et al. 1999).

4 TESTING FOR BIASED STRUCTURAL RESPONSE

To detect potential bias from ground motion scaling, we are interested in examining trends between ground motion scale factors and the resulting structural response. Figure 3 presents results from the records selected and scaled to match *Sa*(0.8s) = 0.6g. Each sub-figure shows structural response levels and scale factors associated with one record-selection method. Linear least-squares regression (applied to the logarithms of the variables) is used to estimate the relationship between these two values. If the regression line has a slope of zero, then records with large scale factors are unbiased (i.e., the mean estimated response is independent of record scale factors). A visual inspection of Figure 3 suggests that the record sets selected with the AR Method and the MR-BR Method show some bias, while the record sets selected with the ε-BR Method and the CMS-ε Method show no bias.

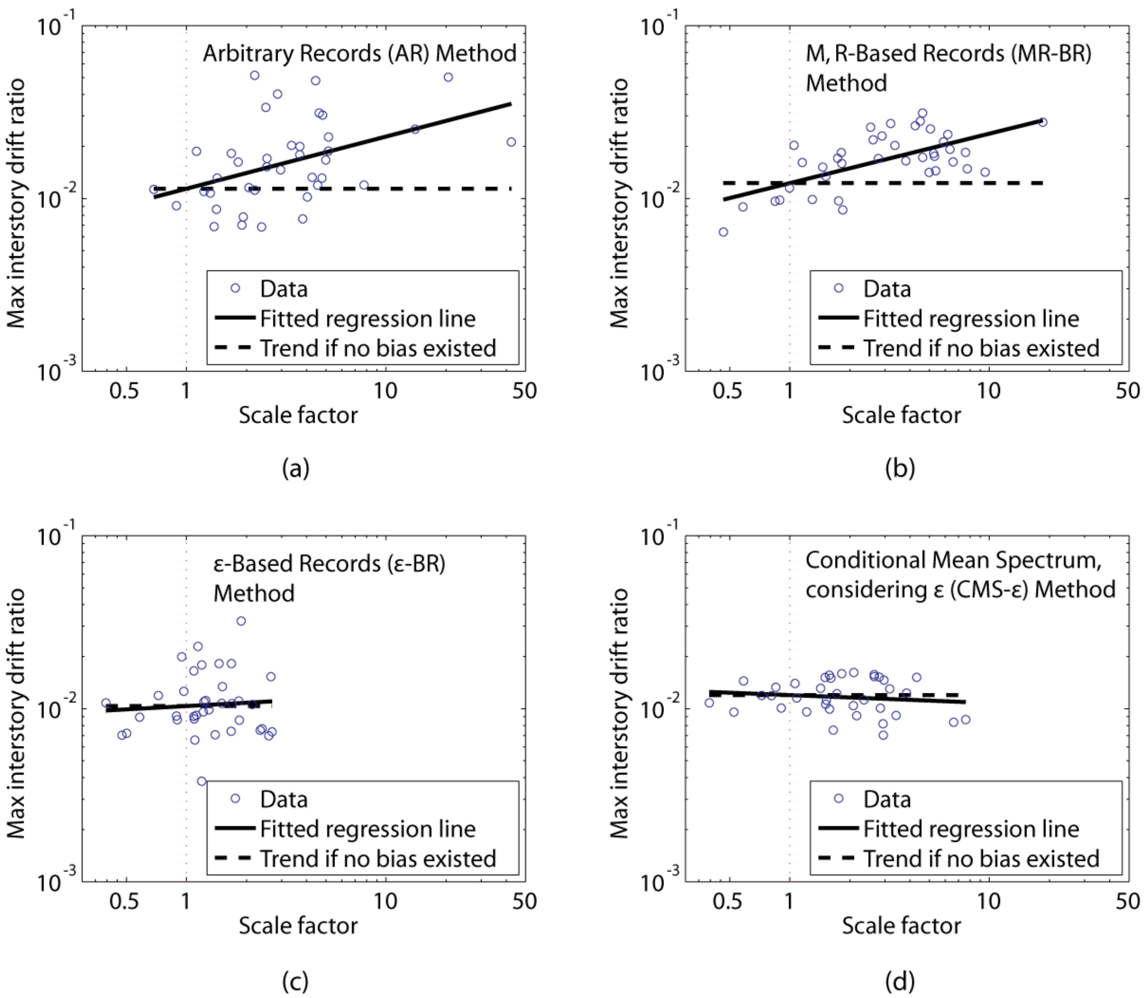

Figure 3: Maximum interstory drift ratio versus record scale factor for each of the four selection methods considered, at an *Sa*(0.8s) level of 0.6g. Regression fits based on scale factor are shown with solid lines. Dashed horizontal lines corresponding to the mean prediction at a scale factor of one are shown for comparison. (a) Records using the AR Method. (b) Records using the MR-BR Method. (c) Records using the ε-BR Method. (d) Records using the CMS-ε Method.

The significance of the slopes from the regression analyses of Figure 3 can be measured using a common statistical diagnostic tool known as an F-test (Kutner et al. 2004). This test produces a probability (referred to as a p-value) that the estimated slope would be as large as, or larger than, the observed slope, given that there was actually no underlying trend in the data (i.e., the probability of erroneously estimating a given slope due to an imprecise estimate from a finite data sample). P-values for the four record-selection methods are reported for six *Sa* levels in Table 1. The row of this table associated with *Sa*(0.8s) = 0.6g provides the p-values for the regressions shown in Figure 3. For this *Sa* level, Methods 1 and 2 have low p-values, indicating that the observed trend is statistically significant. The large p-values for the other two methods indicate that there is likely no underlying trend. When examining all levels of *Sa* in this table, Methods 1 and 2 generally show significant trends with scale factor, while Methods 3 and 4 do not. Similar results were observed when the same test was repeated on two additional structures (Baker and Cornell 2005b, Appendix F). Note that these slopes could also be used to specify a limit on scale factors, given a maximum allowable bias. It is easier and safer, however, to simply select records using Methods 3 or 4, to completely avoid scaling bias. The possibility also exists that scaling to match intensity measures other than $Sa(T_1)$ could help avoid scaling bias. These alternatives appear preferable to limiting the allowable scale factor while using an approach known to cause bias.

The conclusion here that inappropriate record scaling (from Methods 1 and 2) can bias estimated structural response supports the concern expressed by others that record scaling might fail to modify all ground motion properties in an appropriate way. Through the exploration of conditional mean response spectra above, we have seen that the frequency content of ground motions does in fact change as the intensity (i.e., $Sa(T_1)$) changes. What may be unexpected for readers, however, is that the frequency content is more affected by the variation of ε than by the variation of magnitude or distance. Further, if we select records with the desired spectral shape through a careful record selection scheme (i.e., ε-BR or CMS-ε selection), then we *can* scale records without inducing bias.

Table 1. P-values from regression prediction of max interstory drift ratio as a function of scale factor for four methods of record selection, at six levels of *Sa*(0.8s). P-values of less than 0.05 (indicating statistically significant bias) are marked in boldface.

Sa(0.8s)	Method 1: Arbitrary Records	Method 2: M, R-Based Records	Method 3: ε-Based Records	Method 4: CMS-ε Method
0.1	**0.00**	**0.01**	0.21	0.68
0.2	**0.01**	0.89	0.33	0.07
0.4	**0.01**	0.46	0.73	0.51
0.6	**0.00**	**0.00**	0.67	0.44
0.8	**0.00**	**0.00**	0.73	0.30
1	**0.05**	**0.04**	0.23	0.37
median p-value	**0.01**	**0.02**	0.50	0.40

5 DISCUSSION AND CONCLUSIONS

An approach has been proposed and evaluated for detecting bias in estimated structural response caused by scaling the amplitude of recorded ground motions. The approach involves selecting a suite of ground motions that have been scaled to all have the same intensity level. The suite of ground motions is then used for structural analysis, and the resulting structural responses associated with each ground motion are plotted versus the scale factor associated with that ground motion. Trends between the two values indicate that the record scaling is causing biased structural response (i.e., that scaled ground motions are causing different levels of structural response than unscaled ground motions). In the example presented here, ground motion intensity was measured by the spectral acceleration at the first-model period of the structure, and the structural response parameter of interest was maximum interstory drift ratio. Linear relationships were observed between the logarithm of the records' scale factors and the associated max interstory drift ratios, so linear least-squares regression on these log values was used to characterize trends.

In order to identify the impact of record selection strategies on potential scaling bias, records were selected using several methods: use arbitrary records, select records to match causal magnitudes and distances, select records to match causal ε values, or select records to match the spectral shape implied by the ground motion's causal magnitude, distance and ε. 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 this implied 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 currently used for design of nuclear facilities, except that the recently-identified effect of ε is not considered in those spectra.

It was observed that the presence of scaling bias depended upon the method used to select the ground motions. If the records were selected to account for the peaked spectral shape of 'rare' ground motions (i.e., using the third or fourth method), then the records could be safely scaled up to represent rare (i.e., high $Sa(T_1)$) ground motions while still producing the same structural response values as unscaled ground motions. If records were selected without paying attention to this peaked spectral shape, then scaled-up ground motions produced (on average) larger levels of structural response than unscaled ground motions naturally at the target $Sa(T_1)$ level.

These results may at first glance appear to conflict with some past studies that did not detect scaling bias when record were scaled to target $Sa(T_1)$ values (Shome et al. 1998, Iervolino and Cornell 2005). The reason for the difference is that those two studies were considering a specific problem where the mean scale factor among all the records in a suite was approximately one. In those cases, where as many records were scaled up as were scaled down, the median observed max interstory drift ratio was unbiased (i.e., approximately equal to the median result from the unscaled records). This is consistent with the above results, which predict that biases from scaled-up and scaled-down records would offset, resulting in unbiased median response when the average scale factor is approximately one. Biased responses were observed in another report when mean scale factors were larger than one (Luco and Bazzurro 2005), consistent with the results reported here. This work furthers the result of Luco and Bazzurro by finding that ε-based record selection can overcome the scaling bias that occurs using other record selection methods.

Results are reported here for only one measure of structural response and one measure of ground motion intensity. Ongoing research using the proposed approach will determine the extent to which the conclusions here can be generalized to other structural response measures and ground motion intensity measures. The Pacific Earthquake Engineering Research (PEER) center's Ground Motion and Selection and Modification working group is also evaluating a broader range of record selection techniques than the four described above (http://peer.berkeley.edu/gmsm/). The quantitative test of scaling bias proposed here will thus aid in providing objective comparisons among the variety of selection and scaling approaches advocated in the scientific literature and professional practice today.

ACKNOWLEDGEMENTS:

This work was supported by the U.S. Geological Survey, under Award Number 07HQAG0129, and 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 funding agencies.

REFERENCES:

American Society of Civil Engineers. 2005. *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*. Structural Engineering Institute, Working Group for Seismic Design Criteria for Nuclear

Facilities. *ASCE/SEI 43-05*. Reston, VA. 81 pp.

Baker J.W., Cornell C.A. 2005a. A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon. *Earthquake Engineering & Structural Dynamics*. Vol. 34 (10): 1193-1217.

Baker J.W., Cornell C.A. 2005b. *Vector-Valued Ground Motion Intensity Measures for Probabilistic Seismic Demand Analysis*. John A. Blume Earthquake Engineering Center. *John A. Blume Earthquake Engineering Center Report No. 150*. Report #150, Stanford, CA, 321 pp.

Baker J.W., Cornell C.A. 2006a. Correlation of Response Spectral Values for Multi-Component Ground Motions. *Bulletin of the Seismological Society of America*. Vol. 96 (1): 215-227.

Baker J.W., Cornell C.A. 2006b. Spectral Shape, Epsilon and Record Selection. *Earthquake Engineering & Structural Dynamics*. Vol. 35 (9): 1077–1095.

Bommer J.J., Scott S.G., Sarma S.K. 2000. Hazard-Consistent Earthquake Scenarios. *Soil Dynamics and Earthquake Engineering*. Vol. 19: 219-231.

Department of Energy. 1996. *Guidelines for Use of Probabilistic Seismic Hazard Curves at Department of Energy Sites for Department of Energy Facilities*. *Standard DOE-1024-92*.

Han S.W., Wen Y.K. 1994. *Method of Reliability-Based Calibration of Seismic Structural Parameters.* University of Illinois and Urbana-Champaign. UIUC-ENG-94 2016, Stuctural Research Series No. 595, Champaign, IL, 170 pp.

Iervolino I., Cornell C.A. 2005. Record Selection for Nonlinear Seismic Analysis of Structures. *Earthquake Spectra*. Vol. 21 (3): 685-713.

Jalayer F. 2003. *Direct Probabilistic Seismic Analysis: Implementing Non-Linear Dynamic Assessments*. Stanford University. *Ph.D. Thesis*. Stanford, CA. 244 pp.

Krawinkler H. 2004. *Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment*. Pacific Earthquake Engineering Research Center, University of California at Berkeley. PEER 2005-11, Berkeley, California.

Kutner M.H., Nachtsheim C., Neter J. 2004. *Applied Linear Regression Models*. McGraw-Hill/Irwin. Boston ; New York. 701 p. pp.

Luco N., Bazzurro P. 2005. *Effects of Earthquake Record Scaling on Nonlinear Structural Response*. PEER Lifelines Program. *Report on PEER-LL Program Task 1G00 Addendum (Sub-task 1 of 3)*, 64 pp.

McGuire R.K. 1995. Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop. *Bulletin of the Seismological Society of America*. Vol. 85 (5): 1275-1284.

McGuire R.K. 2004. *Seismic Hazard and Risk Analysis*. Earthquake Engineering Research Institute. Berkeley. 240 pp.

Naeim F., Lew M. 1995. On the Use of Design Spectrum Compatible Time Histories. *Earthquake Spectra*. Vol. 11 (1): 111-127.

Nuclear Regulatory Commision. 1997. *Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion*. *Regulatory Guide 1.165*.

Pincheira J.A., Dotiwala F.S., D'Souza J.T. 1999. Seismic Analysis of Older Reinforced Concrete Columns. *Earthquake Spectra*. Vol. 15 (2): 245-272.

Reiter L. 1990. *Earthquake Hazard Analysis: Issues and Insights*. Columbia University Press. New York. 254 pp.

Shome N., Cornell C.A., Bazzurro P., Carballo J.E. 1998. Earthquakes, Records, and Nonlinear Responses. *Earthquake Spectra*. Vol. 14 (3): 469-500.

Watson-Lamprey J., Abrahamson N.A. 2006. Selection of Ground Motion Time Series and Limits on Scaling. *Soil Dynamics and Earthquake Engineering*. Vol. 26 (5): 477-482.