Assessment of Ground Motion Selection and Modification (GMSM) methods for non-linear dynamic analyses of structures

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ABSTRACT

As non-linear response history analyses are becoming more prevalent in practice, there is a need to better understand how the selection and modification (e.g., amplitude scaling or spectrum matching) of records will influence the resulting structural response predictions. There are currently many methods of ground motion selection and modification available, but little guidance is available to engineers on which methods are appropriate for their specific application. The Ground Motion Selection and Modification Program was formed within the Pacific Earthquake Engineering Research (PEER) Center to address this issue. This paper presents the current methodology developed by the Program as well as sample results from the first pilot study completed in 2006. Preliminary results show that for a first-mode-dominated structure, one can improve the prediction of its response by taking into account record properties that are important to the non-linear response of the building when selecting and scaling ground motion records.

INTRODUCTION

There are currently many methods of ground motion selection and modification (GMSM) available for use in dynamic analyses. Unfortunately, there is no consensus as to the accuracy and precision of these methods in predicting the structural response, thus the choice of which method to use remains largely subjective. This has a significant impact on the engineering community since non-linear response is sensitive to the selection and modification of input ground motions.

The Ground Motion Selection and Modification (GMSM) Program was formed to confront these issues (http://peer.berkeley.edu/gmsm/). One of the main objectives of the GMSM Program is to systematically review different GMSM procedures, and evaluate their respective accuracy and precision in predicting nonlinear dynamic structural responses. As a central part of this effort, the GMSM Program is currently collaborating with over 20 researchers and practitioners in the fields of Earthquake Engineering and Seismology. The list of collaborators includes several who are contributing to the development of new performance-based design criteria as part of the PEER Tall Buildings Initiative (http://peer.berkeley.edu/tbi/). The program intends for its results to become an important resource for engineers using non-linear dynamic analyses in their projects.

GMSM METHODS

The first task of the GMSM Program was to compile a list of existing GMSM methods. To date a list of over 40 different methods and variants has been developed.

In order to compare the methods in a consistent manner, they were first grouped according to their objective. Some methods aim to estimate the average (or median) structural response for a given earthquake scenario, whereas others also attempt to estimate the corresponding variability in structural response. For some methods, the earthquake scenario is defined by only its magnitude and distance to the location of the structure (as well as other characteristics of the rupture and site in some cases), whereas for others the ground motion amplitude (e.g., spectral acceleration at the fundamental period of the structure) at the location is additionally specified. Each of these cases are being considered in this overall effort, but this paper focuses on methods for which the objective is prediction of the median structural response for a given earthquake magnitude, source-to-site distance and a ground motion amplitude parameter.

In order to organize the comparison of results, these methods have also been grouped into the following general categories:

- Methods based on scaling to a Uniform Hazard Spectrum (UHS) associated with the target spectral acceleration of the first-mode of the structure, $Sa(T_1)$. These methods include the approach prevalent in current building codes (e.g., ASCE Standard 7-05, 2005).

- Methods that take into account the record properties that tangibly affect the non-linear response of the structure. These methods include those based on spectral shape, and those that account for the non-linear response through record properties other than spectral acceleration.

To date, the only GMSM methods studied in detail are those that directly scale existing records. Spectrum-compatible motions and synthetic motions will be addressed in later studies.

METHODOLOGY OVERVIEW

The GMSM Program is working toward systematically assessing many different GMSM methods for multiple earthquake scenarios and a large variety of non-linear structures, including buildings, bridges, earth dams, nuclear power-plants, etc. To this end, the GMSM Program is currently working on a set of pilot studies, each with the same basic methodology. This section explains the assessment methodology used in the Program, as applied to the first pilot study, which was initiated in 2006. In this study, the non-linear response of a code-conforming four-story reinforced concrete frame building was analyzed for a deterministic seismic event. The structural model used in the initial analysis was developed at Stanford University for the collaborative "PEER Benchmark Project" with researchers at the University of California at Los Angeles and the California Institute of Technology (Goulet et al. 2007). For the second phase of studies, initiated in 2007, three additional structural models were introduced and the methodology was applied in the same manner. The goal of these studies is to determine which GMSM methods produce unbiased estimates of structural response parameters with low standard error, and to understand what elements of these methods contribute to a better prediction. Once this is determined, predicting the full distribution of response will then be addressed by the Program.

Earthquake Scenarios

The choice of earthquake scenarios was dictated by an interest in the practical relevance of the findings of this study. The first event considered is a strike-slip fault rupture, magnitude 7 earthquake, 10 km from a site with a V_{s30} of 400 m/s (average shear wave velocity of the upper 30 meters of the soil column). A second similar scenario event of magnitude 7.5 was also defined for the same site conditions and style of faulting. In California, a magnitude 7 or 7.5 event within 20 km is often a hazard-controlling source and the site condition represents an average stiffness for alluvial deposits in urban areas. In an effort to push the structural response well into the non-linear range, the target ground motion level for the M7 event has been defined as the 98th percentile prediction, which is equivalent to the median plus two standard deviations, or an epsilon (ε) value of 2. Another reason to use $\varepsilon = 2$ is that the relatively large epsilon leads to a more significant difference between those methods that take epsilon (or another indicator of spectral shape) into account and those that do not. Epsilon values around 2 are also not uncommon for seismic hazard in California at or beyond the 2% in 50 year exceedance code requirement. For the second M7.5 scenario, the 84th percentile is used (equivalent to $\varepsilon = 1$), which is consistent with the deterministic ground motions currently used for design near many major faults. Results for both scenarios (M=7, $\varepsilon = 2$ and M=7.5, $\varepsilon = 1$) will be compared for a selected structure in an effort to generalize the results.

Structural Models

Table A shows the structural models developed for these systematic studies. The four building models considered so far are all reinforced-concrete structures. Buildings A, B and C are modeled in OpenSees (OpenSees, 2007) and building D is modeled in Drain-2DX (Prakash et. al. 1993). Additional information regarding the models can be found in Haselton (2006) and Zareian (2006). While selecting structures, there was a desire to cover a range of height and number of stories (and first-mode period (T_1)), and varying expected levels of non-linearity in the structure. All the structures were analyzed for the M7, ε =2 scenario. Structure C was also analyzed for the M7.5, ε =1 scenario. The shear-wall structure (D) was chosen to be 12 stories tall for comparison with the 12-story frame (B). Although there are differences in the modeling details between the OpenSees and the Drain models, it is interesting to compare the two general structural types. For reasons of brevity, this paper shows only the results for building A with the M7, ε =2 scenario.

Table A. Summary of structural models

Building	*Stories*	*Type*	*Compliance*	T_1^* *(s)*
A	4	Modern special moment frame	2003 IBC, ASCE7-02, ACI 318-02	0.97
B	12	Modern special moment frame	2003 IBC, ASCE7-02, ACI 318-02	2.01
C	20	Modern special moment frame	2003 IBC, ASCE7-02, ACI 318-02	2.63
D	12	Modern (ductile) planar shear wall	None specifically, but consistent with modern planar wall design	1.20

* First-mode natural period.

GMSM Suite Solicitation

Ground motion records were solicited from GMSM method developers and users. The contributors were asked to provide suites of seven ground motions selected and scaled to predict median structural response given the magnitude 7 earthquake at a distance of 10 km from the site defined earlier and 98th percentile spectral acceleration at the fundamental period of the structure. The initial choice of requesting seven records was based on building code requirements (ASCE 2005). For the first round (building A), 112 time series, comprising 16 suites of ground motion records were submitted.

For the second study, the request was for four independent sets of seven time series for each structure and earthquake scenario. Each set of seven records is used to predict the median structural response, and the difference in prediction between sets is noted. In addition, the combined set of 28 records will be used to estimate both the median and standard deviation of response conditioned on the given event. This will allow the group to address the question of the minimum number of ground motions that should be used to efficiently and sufficiently predict the response.

The Point of Comparison

A point of comparison for the median structural response conditioned on 98th percentile ground motion (spectral acceleration) at the fundamental period of the structure for the specified earthquake is calculated using a large suite of earthquake records corresponding to the desired earthquake scenario. An extensive set of structural simulations is performed for this suite of records consistent with the specified earthquake scaled by factors of 1, 2, 4 and 8. A regression is then performed, which takes into account spectral shape and removes the effects of scaling bias. This regression is used to obtain a probability distribution for the Engineering Demand Parameter (EDP) of interest. The point of comparison analysis takes into account differences in spectral shape, magnitude, distance and other record properties. Additional information regarding this procedure can be found in Watson-Lamprey (2007). Figure 1 shows the predicted probability density function for the maximum inter-story drift ratio (MIDR) of Building A. The MIDR is the EDP of interest in this paper, and the median prediction below is used as a point of comparison for the predictions of all the GMSM methods being considered.

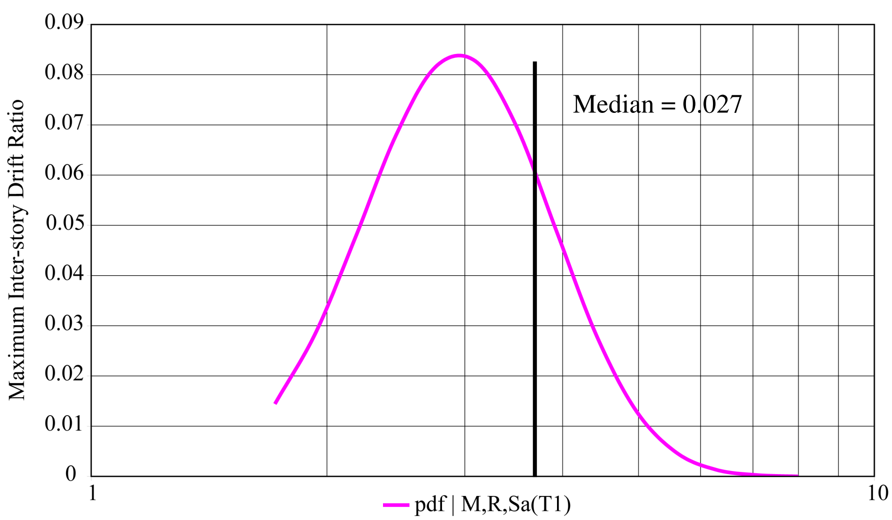

FIG. 1. Probability density function for maximum inter-story drift ratio of building A for the M7 deterministic earthquake scenario.

SAMPLE RESULTS

The following results are for building A for the M=7, ε =2 scenario. The maximum inter-story drift ratios (MIDR) for each of the ground motion records submitted for building A are shown on Figure 2. The median of the seven MIDR values is shown as a long dash for each method, while the red line represents the point of comparison value of 0.027. There is large scatter in the MIDR values predicted for each ground motion of a single ground motion suite, and there is also large variability in the median predicted values from each suite.

Methods 1 through 10 all fall in the first group of methods: those based on scaling to a UHS, such as in code-based methods. The results from suites 1 through 10 exhibit a large scatter. They also tend to overestimate the median response. All these suites matched, on average, the 98th-percentile random horizontal ground motion elastic response spectrum, but recall that the median MIDR of interest is conditioned on only the spectral value at the first mode.

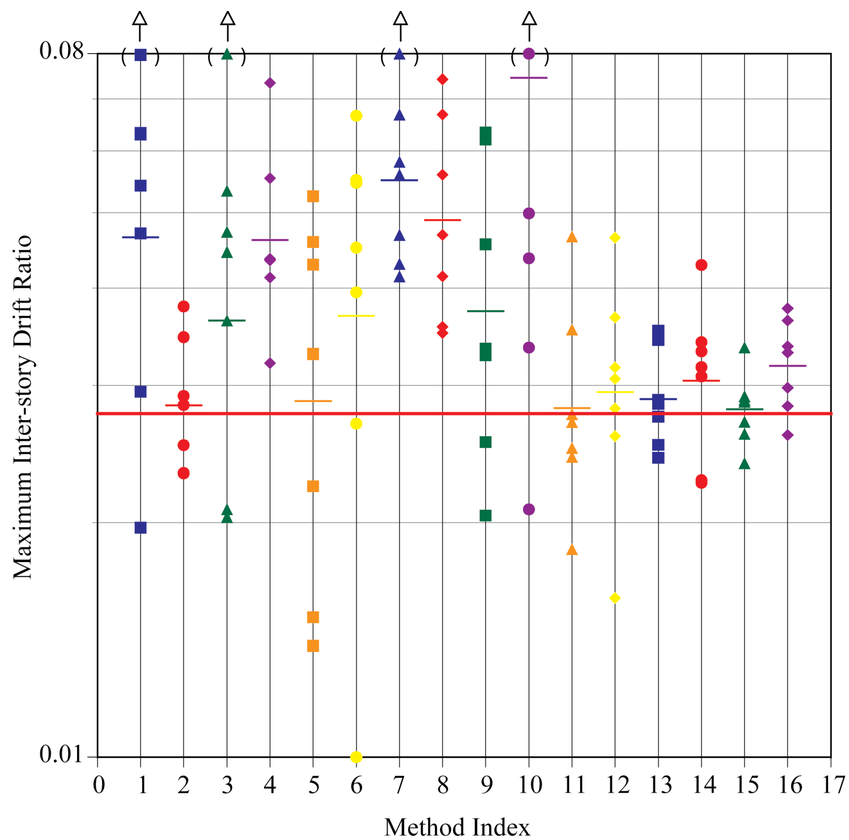

FIG. 2. Summary of results for ground motions submitted, building A. The horizontal red line represents the point of comparison.

Since the structure is non-linear, the *effective* first mode period increases as it yields. The spectral shape beyond the original fundamental period is therefore important when predicting MIDR. The expected response spectrum for a given set of magnitude, distance and ε or *Sa(T)* values is called the conditional mean spectrum (CMS). Computation of the condition mean spectrum requires knowledge of a mean and standard deviation of logarithmic spectral acceleration at all periods, as given by a ground motion prediction (attenuation) model, and a target magnitude, distance and "*ε*" value from either a target scenario or a probabilistic seismic hazard analysis disaggregation. In addition, the knowledge of correlations between *Sa* values at two periods is required, which is available in the form of an analytical predictive equation obtained from empirical studies (Baker and Cornell 2006). The CMS for structure A is shown on Figure 3. The spectral shape beyond the fundamental period conditioned on the 98th percentile values is lower than the 98th percentile spectrum, as indicated by the CMS. In effect, these suites (1 through 10) were attempting to predict the response from a more extreme realization of earthquake ground motions. The CMS was identified as an important part of many GMSM methods and was thus included in the second-phase solicitation sent out in 2007.

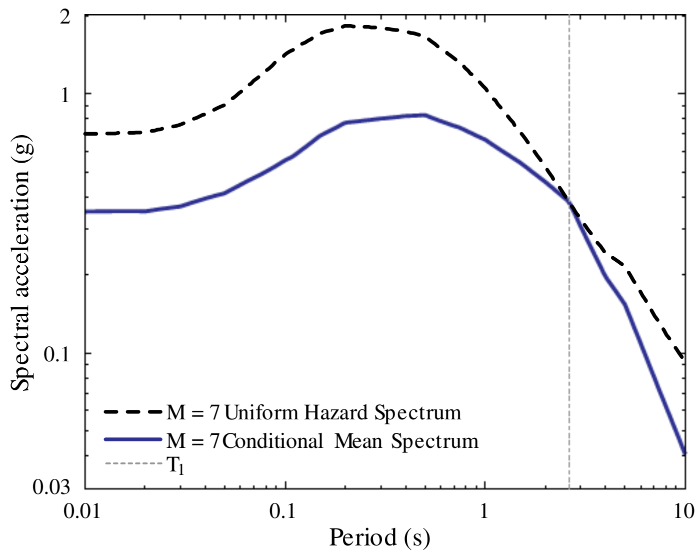

FIG. 3. Conditional mean and uniform hazard spectra for M7, ε =2 scenario, building A.

Methods 11 through 16, on the other hand, incorporate record properties that tangibly affect the non-linear response of the structure. Some by either tracking the expected spectral shape or selecting/scaling based on the expected values of other record properties that are important for non-linear response. These suites exhibit much smaller dispersion and appear to provide estimates of the median maximum inter-story drift ratio with a greater degree of accuracy.

Examples of Spectra Obtained from Two Methods

The different scaled spectra for method 9 are shown in Figure 4 as a representative example of the first group of methods. This method over-predicted the MIDR by about 30% relative to the point of comparison. There is a large scatter in the spectra, but they match on average the target 98^{th}-percentile ground motion from short periods up to a period of approximately three seconds.

Figure 5 shows the scaled spectra for method 15. This suite predicted the median maximum inter-story drift ratio within 1% of the point of comparison. The spectra for method 15 only match the 98^{th}-percentile predicted ground motion at the fundamental period. There is a smaller scatter in the spectra beyond the fundamental period compared to method 9 (Figure 4) and, on average, the spectra fall lower on the graph.

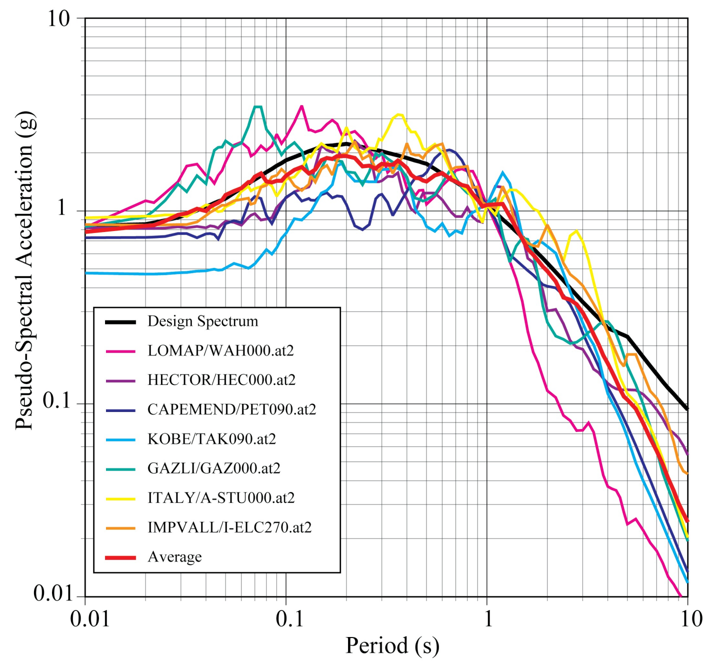

FIG. 4. Example of scaled spectra for method 9.

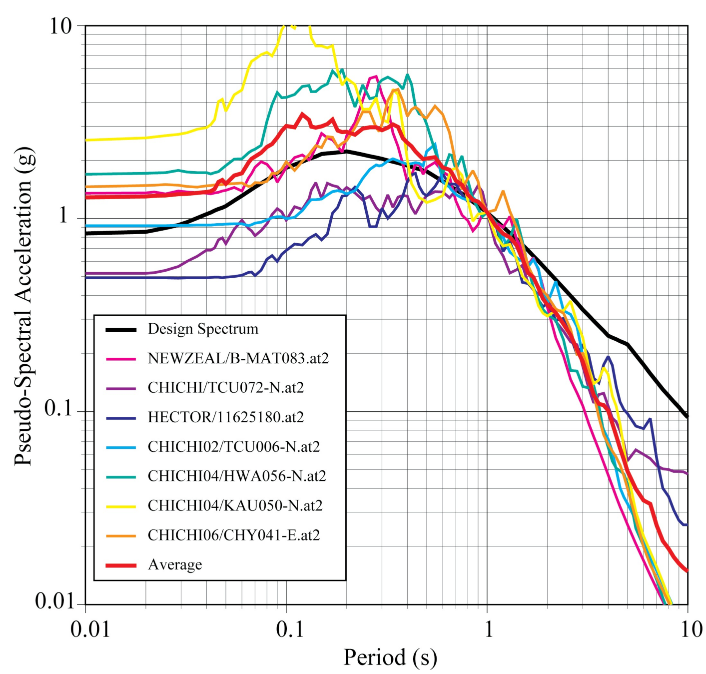

FIG. 5. Example of scaled spectra for method 15.

It is interesting to note that although these differences in spectral shape might be considered rather small, they do have an important consequence on the median MIDR predictions (overestimation by 30% in one case and within 1% in the other).

CONCLUSIONS AND FUTURE EFFORTS

The paper presented an overview of the current GMSM Program methodology for evaluating ground motion selection and modification methods for non-linear structural dynamic analyses. Sample results from the first pilot study have also been presented. These preliminary results show that GMSM methods that consider ground motion properties that tangibly affect the non-linear response of the structure tend to offer a better prediction of the maximum inter-story drift ratio. These methods provide a better median prediction, relative to the point of comparison, with a smaller dispersion.

Evaluating predictions of median structural response parameters for buildings is an important first step towards identifying appropriate ground motion record selection and modification methods, but MIDR is not the only response quantity of interest, nor are buildings the only application for non-linear dynamic analysis. The GMSM Program plans to generalize these findings and provide the engineering community with GMSM recommendations. This will involve future work in performing similar evaluations for prediction of variability in structural response, looking at additional response quantities such as peak floor accelerations and peak base shear, and performing comparisons for other types of systems for which non-linear dynamic analysis is performed (e.g. bridges, dams, nuclear power-plants, etc.).

The GMSM Program is currently evaluating GMSM methods for the three newly-added structures (buildings B, C and D). The results from this wider range of structural types will expand and generalize the findings of this paper, and ensure that the conclusions drawn from the overall study will be valid under more general conditions. Future efforts will continue widening the range of structures analyzed, and extend the methodology for study of spectrum-matched and simulated ground motions.

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