13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2007

EFEFCTS OF GROUND MOTION UNCERTAINTY ON PREDICTING THE RESPONSE OF AN EXISTING RC FRAME STRUCTURE

Fatemeh JALAYER[1], James L. BECK[2], Keith A. PORTER[3] and John F. HALL[4]

SUMMARY

Estimation of structural response may be significantly affected by the representation of seismic ground motion uncertainty. A complete probabilistic presentation of ground motion can be constructed by specifying a stochastic model that depends on seismic source parameters. Alternatively, the ground motion uncertainty can be represented by adopting parameters known as the intensity measures (IM), and using attenuation relationships to relate the IM to seismic source parameters. The uncertainty in the prediction of structural response can be expressed in terms of the probability of exceeding a given value of the structural response. In this study, the uncertainty in the ground motion is represented in these two alternative ways: (a) a full probabilistic representation using an advanced simulation technique known as subset simulation (Au [4]) based on a stochastic ground motion model conditional on magnitude and distance proposed by Atkinson and Silva (Atkinson [3]), and, (b) by adopting spectral acceleration at the small amplitude fundamental period as the intensity measure. In alternative (b), a suite of ground motion recordings are used to represent ground motion characteristics not already captured by the IM. The attenuation relation relating the IM to the seismic source parameters is obtained by two alternative approaches: (i) by simulating stochastic ground motions and applying them to an elastic SDOF system and (ii) by using the empirical regression equation of Abrahamson and Silva (1997). The alternative approaches are compared based on their prediction of the uncertainty in structural response. Another comparison is done between the following two cases: (1) by predicting the structural response following alternative (b) and using a suite of real ground motion recordings and (2) by predicting the structural response following alternative (b) and using a suite of synthetic records. The suite of synthetic records are generated according to the same stochastic model used in alternative (a) for a given magnitude and distance; this provides a common basis for comparisons. In order to emulate selection of a suite of real records from a bin, alternative (a) and case (2) of alternative (b) described above are repeated using a suite of synthetic records generated for magnitude and distance as uncertain variables belonging to a designated bin. An existing 7-story reinforced concrete structure is used as a case-study. The structural model (Jalayer [9]) includes stiffness and strength degradation.

[1] George W. Housner Research Fellow, California Institute of Technology
[2] Professor, California Institute of Technology
[3] George W. Housner Senior Research Fellow, California Institute of Technology
[4] Professor, California Institute of Technology

INTRODUCTION

One of the main attributes distinguishing performance-based earthquake engineering from traditional earthquake engineering is the definition of quantifiable performance objectives. The performance objectives are quantified usually based on life-cycle cost considerations, which encompass various parameters affecting structural performance, such as, structural, non-structural or contents damage, and human casualties. Apart from being rare events and having large consequences, earthquakes also have large uncertainty associated with them. There are alternative ways to represent this uncertainty for design and assessment of structures. Most of the current seismic design procedures (FEMA 356 [7], ATC-40 [2]) take into account the uncertainty in the ground motion implicitly by defining “design earthquakes” with prescribed probabilities of being exceeded in a given time period. In the recent years, specifically after the 1994 Northridge Earthquake, considerable research effort has been focused on defining probabilistic performance objectives that balance desirable structural performance and life cycle costs (Wen, [13]). A performance objective can be expressed in terms of the probability of exceeding a specified limit state defined in terms of life cycle cost or some other structural performance parameter. Probabilistic performance objectives, by definition, take into consideration the uncertainty in the ground motion. However, there are alternative ways for representing ground motion uncertainty.

One way to represent ground motion uncertainty is by adopting a parameter (or a vector of parameters) known as the intensity measure (IM) in order to represent the uncertainty in the ground motion. The adopted IM is also used to scale a suite of ground motion recordings (around ~20-30) in order to capture ground motion uncertainty not captured by the IM itself. The advantage of such representation of ground motion, which has been proposed for existing performance-based design procedures, is that is takes into account the uncertainty in the ground motion in two stages, namely, the ground motion level and structural response level, in a more-or-less un-coupled manner. The other advantage of this IM-based approach is that it can be devised with fairly small number of structural analyses (if structural model uncertainty is ignored). This advantage, however, can also be interpreted as a weakness of such representation; since it cannot provide a full probabilistic representation of the ground motion with such a small number of ground recordings. Moreover, the amount of its deviation from true probabilistic representation of the ground motion cannot be quantified. The alternative way to represent the uncertainty in the ground motion is by a complete probabilistic representation of the ground motion. In a way, this representation is the limiting case of the IM-based one, in that the ground motion time history can be thought of as a vector IM with stochastic components. This probabilistic representation is based on a stochastic ground motion model conditional on seismic source parameters. The main advantage of this representation is that it provides a full probabilistic representation of ground motion and hence of structural response. However, it requires considerable number of structural analyses. The number of required structural analyses can be significantly reduced by using efficient simulation routines such as subset simulation (Au [4], [5]) or a very efficient importance sampling method called ISEE (Au [6]). The main weakness of this method lies in its dependence on a stochastic ground motion model to provide a realistic description of the characteristics of the ground motions expected to happen.

This paper summarizes a preliminary effort for benchmarking the alternative representations of ground motion for a scenario earthquake (i.e., fixed M and r) with regard to their prediction of structural response. More specifically, the performance objective is expressed in terms of the probability that a designated structural response parameter (here, maximum inter-story drift ratio) exceeds a specified value. In order to provide a common basis for comparing the two different representations, the stochastic ground motions are also employed in the IM-based approach. This allows for comparing the two representations separate from the differences between real and synthetic ground motion recordings. In order to emulate selection of a suite of real recordings from a bin representing a scenario earthquake, structural response predictions are repeated using a suite of synthetic records generated when magnitude and distance are uncertain variables from a designated magnitude-distance bin.

An existing seven story hotel located in Van Nuys, California, is used as a case-study. It is modeled as a reinforced concrete structure with degrading behavior in the nonlinear range. Maximum inter-story drift ratio denoted by, $\theta_{\max}$, is used as the designated structural response parameter; and the spectral acceleration at the fundamental period, $S_a(T_1 = 0.80\,\text{sec})$, is adopted as the ground motion intensity measure.

MODEL STRUCTURE: TRANSVERSE FRAME OF AN EXISTING BUILDING

One of the transverse frames in the hotel structure located in Van Nuys is selected for the structural model (Figure 1). This building is an older reinforced concrete (RC) structure that suffered shear failures in its columns during the 1994 Northridge Earthquake. The frame is modeled using DRAIN2D-UW, which is a modified version of DRAIN2D produced at the University of Wisconsin (see Pincheira [11]). The structural model takes into account stiffness and strength degrading behavior in the non-linear range for both flexure and shear (see Jalayer, 2003 for more details).

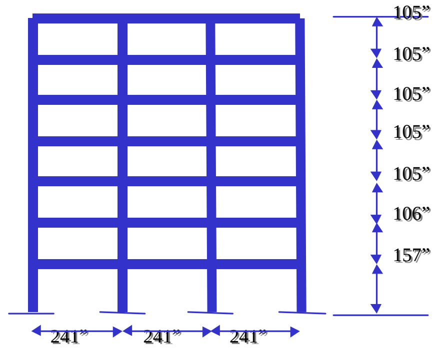

Figure 1. Structural Model

SUBSET SIMULATION PROCEDURE- AN EFFICIENT SIMULATION TECHNIQUE

Subset simulation (Au [4], [5]) is a simulation procedure used for efficiently computing probabilities of rare events, such as the seismic risk for a structural system. Subset simulation is based on the idea that small probabilities can be expressed as the product of larger conditional probabilities. This helps to break the simulation of a rare event into a sequence of simulations of more frequent events that are conditioned on failing successively increasing threshold levels. Subset simulation can be preformed with significantly smaller number of structural analyses compared to standard Monte Carlo simulation. Subset simulation technique can be employed for assessing the reliability of both linear and non-linear dynamic systems. Various sources of uncertainty, such as the uncertainty in the input or modeling uncertainty can be introduced into the reliability problem solved by subset simulation.

This paper employs the subset simulation technique for both obtaining a probabilistic estimate of the structural response and also that of the adopted intensity measure. It is assumed that the uncertainty in the input, here ground motion uncertainty, is the only source of uncertainty. However, as mentioned above, this routine is general with respect to the sources of uncertainty introduced into the assessments. The stochastic ground motion model introduced by Atkinson and Silva (Atkinson [3]) is employed in order to describe the seismic source characteristics for a scenario earthquake.

ATKINSON AND SILVA (2000) STOCHASTIC GROUND MOTION MODEL

A stochastic ground motion model may be used to describe the ground motion at the site for a scenario event with given magnitude and distance from the site. This paper adopts the stochastic point-source ground motion model developed by Atkinson and Silva (2000) for California ground motions recorded on rock sites. In order to generate a ground motion time history to be employed in a Monte Carlo simulation procedure, a sequence of independent and identically distributed standard Normal variables (white noise) at discrete time intervals are modulated by an envelope function. The resulting modulated white noise sequence is transformed into the frequency domain using the discrete Fourier transform and then multiplied by the radiation spectrum defined by the ground motion model. This results in a spectrum that on average agrees with the radiation spectrum defined by the ground motion model. Finally, the inverse Fourier transform is used to bring the resulting spectrum back into the time domain. It should also be noted that amplifications for a soil site is considered by applying empirical soil factors provided by Abrahamson and Silva (1997) (Abrahamson [1]) to the relations derived for rock sites.

EFFECT OF GROUND MOTION UNCERTAINTY ON PROBABILISTIC IM PREDICTION FOR A SCENARIO EARTHQUAKE

A preliminary step for comparing alternative representations of ground motion uncertainty is by benchmarking the predictions of the intensity measure (IM) for a scenario earthquake with specified magnitude and distance. In the IM-based representation of ground motion, empirical attenuation relations are used to predict the mean and standard deviation of the intensity measure for a given value of the magnitude and distance. In the alternative representation, simulation techniques may be employed to provide a full probabilistic distribution of the adopted intensity measure for a given magnitude and distance based on a stochastic ground motion model.

In order to bridge between these two ground motion representations, the full probabilistic approach can be used to obtain a “synthetic” attenuation relation based on the generated stochastic ground motion records. This can be done by designating the IM itself as a response parameter and obtaining its probabilistic distribution for a given scenario event. This exercise is useful for providing a common basis for comparing the two representations.

Empirical Attenuation Relations

The (adopted) intensity measure can be predicted for a given magnitude and distance using empirical attenuation models that are developed from a database of ground motion records. The relation between IM and ground motion parameters, such as magnitude and distance, can be expressed in the following generic form:

$$\ln IM = f(M,r) + \varepsilon \cdot \sigma_{\ln IM|M,r} \qquad \text{Eq. 1}$$

Here, $\ln IM$ denotes the natural logarithm of IM, M denotes moment magnitude, and r denotes distance from the site. The functional form $f(.)$ predicts the mean of $\ln IM$ for a given magnitude, distance, style of faulting, and soil condition of the site. This functional form is determined using a regression model to fit a database of real ground motion recordings. $\sigma_{\ln IM|M,r}$ denotes the standard error of the regression for a given magnitude and distance. It is used to estimate the standard deviation of $\ln IM$ for a given magnitude and distance. ε is the normalized prediction error (usually assumed to be a standard Normal variable) denoting the number of standard deviations $\ln IM$ differs from its mean estimate provided by the empirical attenuation model.

Abrahamson and Silva (1997) Empirical Attenuation Relation

In this paper, the spectral acceleration at the small-amplitude fundamental period of the structure, $T_1 = 0.80$ sec, denoted by $S_a(T_1)$ or simply S_a, is adopted as the intensity measure (IM). The empirical response spectral attenuation relations developed by Abrahamson [1] for shallow crustal earthquakes are used for representing the uncertainty in the spectral acceleration for a given scenario earthquake. The spectral acceleration is described by a log-normal distribution. The parameters of this distribution, namely, mean and standard deviation, are predicted by the attenuation relation. Figure 2 illustrates (solid line) the probability of exceeding a given value of spectral acceleration calculated from the Abrahamson and Silva (1997) attenuation relation at a period of $T = 0.75$ sec, the closest listed value to the fundamental period of the model structure, for a strike-slip earthquake event with, $M = 7$, $r = 20\,km$, recorded on deep soil.

Synthetic Attenuation Relation Based on Atkinson and Silva (2000) Model

An alternative way to develop an attenuation relation for a given scenario event is to derive it from the stochastic ground motion model using an efficient simulation technique (here, subset simulation) in order to obtain a probability distribution for the spectral response of an elastic SDOF system. In this paper, the resulting probability distribution for S_a is also referred to as the "synthetic" attenuation relation; in order to distinguish it from the "empirical" attenuation relation. Figure 2 illustrates (dashed line) the probability of exceeding a given value of S_a obtained using subset simulation technique with 2300 samples and the Atkinson and Silva (2000) stochastic ground motion model. This plot gives the probability distribution for the spectral response of an elastic SDOF system with 5% damping at $T = 0.80$ sec for a scenario event with $M = 7$ and $r = 20\,km$ recorded on deep soil.

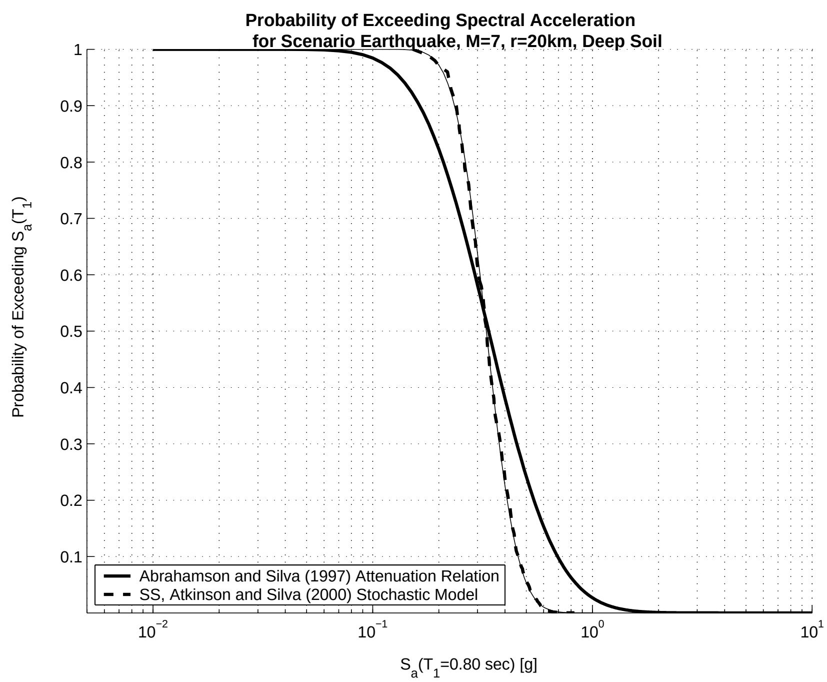

Figure 2- Effect of the Alternative Representations of Ground Motion Uncertainty on the Prediction of the Spectral Acceleration at the Fundamental Period of the Structure

Observations

It can be observed from Figure 2 that the probability distribution for S_a based on the empirical attenuation relation (the solid line) spans over a wider range of spectral acceleration values compared to the one provided by the synthetic attenuation relation (the dashed line). In order to compare the two curves more quantitatively, a lognormal probability distribution (thin solid line) with median (0.33g) and standard deviation of $\ln S_a$ (0.26) equal to the synthetic attenuation relation (dashed line) is also plotted. It can be observed that the lognormal distribution describes perfectly the synthetic attenuation relation. Since the empirical attenuation relation itself is described by a lognormal distribution with median equal to 0.34g and standard deviation of the logarithm equal to 0.56, one can compare the empirical and synthetic attenuation relations by comparing the median and the standard deviation of the logarithm of the corresponding lognormal probability distributions. It is observed that the median spectral accelerations from the synthetic and empirical attenuation relations are very close to each other, but the standard deviation of $\ln S_a$ according to the empirical attenuation relation is more than twice that of the synthetic relation.

EFFECT OF GROUND MOTION UNCERTAINTY REPRESENTATION ON PROBABILISTIC STRUCTURAL RESPONSE PREDICTION FOR A SCENARIO EARTHQUAKE

In the previous section, alternative ground motion representations and their effect on probabilistic predictions of the intensity measure S_a were studied. In a similar manner, this section looks into the effect of ground motion uncertainty representation on prediction of structural response. The discussions are divided into four categories. The first category describes structural response predictions using a least squares estimate of structural response versus spectral acceleration based on the data provided by a few (e.g., 20) non-linear dynamic analyses of structure subjected to a suite of real ground motion records. In this category, spectral acceleration is related to ground motion parameters by an empirical attenuation relation. The second category describes response predictions using a simulation procedure (subset simulation) based on a stochastic ground motion model. The third category describes response predictions similar to the first category but using non-linear dynamic response to synthetic records and also using a synthetic attenuation relation to relate the spectral acceleration to ground motion parameters. The third category of ground motion representations, which is rarely used in practice, serves as a bridge between the two alternative representations of ground motion and facilitates the comparisons. The last category is dedicated to structural response predictions using synthetic ground motion records as in the second and third category but generated from a designated magnitude-distance bin. This is an effort to emulate the real ground motion selection from a magnitude-distance bin representing a scenario earthquake.

Predicting Structural Response Using IM and Existing Ground Motion Records to Represent Ground Motion Uncertainty

In this approach, the spectral acceleration for a scenario earthquake is predicted by the empirical attenuation relation of Abrahamson and Silva 1997. The next step is to predict the structural response uncertainty for the range of possible values of the spectral acceleration. It has been demonstrated (Jalayer [9]) that several non-linear dynamic analysis procedures can be used to predict the structural response uncertainty conditional on S_a over a range of spectral acceleration values.

One such procedure employs linear regression to data pairs consisting of the logarithm of the structural response and logarithm of spectral acceleration for a suite of real ground motion recordings. Figure 3 illustrates maximum inter-story drift ratios obtained by performing non-linear dynamic analyses on a suite of 20 real ground motion records selected from Pacific Earthquake Engineering Research Center (PEER [12]) database and plotted versus the corresponding spectral acceleration values for the records. These records are all free field recordings on deep soil (soil type D by the Geo-matrix definition, PEER [12]). In order to approximately represent the ground motion corresponding to a scenario event with magnitude 7 and distance 20 km, the records are chosen from a bin of ground motions records with moment magnitude between 6.5 and 7.5 and closest distance to the site between 10 to 30 kilometers.

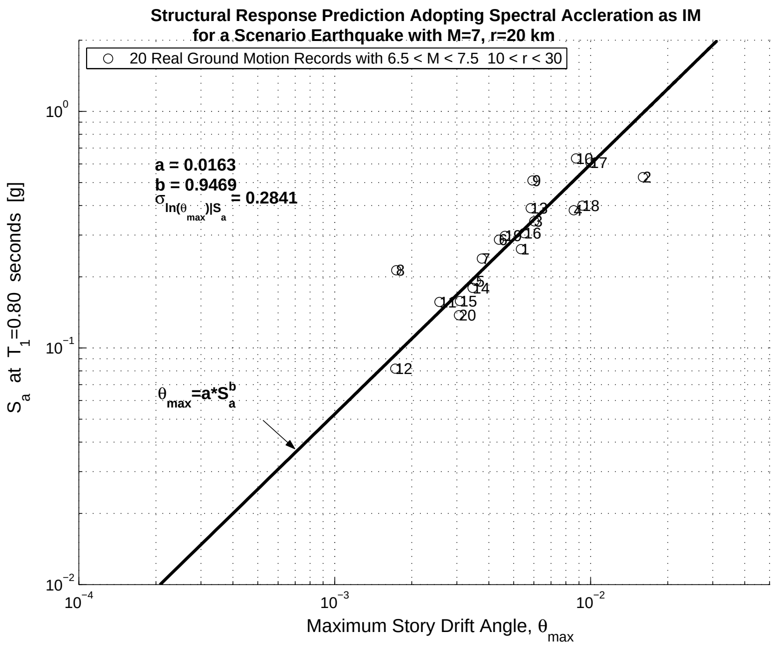

Figure 3. Predicting Structural Response (Maximum Inter-story Drift Angle) for a Suite of Real Ground Motion Records

The data-pairs plotted in Figure 3, are used to provide a conditional probabilistic description of maximum inter-story drift ratio, denoted by $\theta_{\max}$, given the spectral acceleration S_a at the fundamental period of the structure (i.e., the adopted intensity measure). This has been done by least-squares fitting of a line to these points in a logarithmic scale (see Luco [10], Jalayer [8]), which is equivalent to fitting a power-law function, $\theta_{\max} = a \cdot S_a{}^b$, to these points in arithmetic scale. This functional form predicts the conditional mean of the logarithm of maximum inter-story drift ratio for a given spectral acceleration value. Assuming that maximum inter-story drift ratio $\theta_{\max}$ can be described by a lognormal variable with constant standard deviation (i.e., not a function of spectral acceleration), one may use the standard error of the regression to estimate the conditional standard deviation of the logarithm of maximum inter-story drift for a given spectral acceleration ($\sigma_{\ln(\theta_{\max})|S_a} = 0.28$). The probability of $\theta_{\max}$ not exceeding value *x*, conditional on S_a is therefore given by:

$$P[\theta_{\max} \le x \mid S_a] = \Phi\left(\frac{\ln x - \ln a - b \cdot \ln S_a}{\sigma_{\ln(\theta_{\max})|S_a}}\right) \qquad \text{Eq. 2}$$

where Φ is the cumulative distribution function for a standard Normal variable and the parameters in Equation 2 are given in Figure 3.

The uncertainty in the prediction of structural response for a given scenario earthquake can be described by the probability of exceeding a given value of maximum inter-story drift angle, *x*, which can be evaluated numerically using the Total Probability Theorem:

$$P[\theta_{\max} > x \mid M, r] = 1 - \int_0^\infty P[\theta_{\max} \le x \mid S_a] \cdot p(S_a \mid M, r) \cdot dS_a \qquad \text{Eq. 3}$$

This integration combines the lognormal distribution function $p(S_a \mid M, r)$ provided by the empirical attenuation relation, which predicts the spectral acceleration for a given scenario earthquake, and the conditional lognormal distribution of response given spectral acceleration described in Equation 2. Figure 5 illustrates the probability of exceeding a maximum inter-story drift ratio (solid line) for a scenario earthquake of magnitude 7 and distance to site equal to 20 km that is calculated as described. It should be noted that the number of non-linear dynamic analyses used to produce this result is equal to 20, which is the number of ground motion records used for structural response predictions. The probability values in Figure 5 (vertical axis) are shown in the logarithmic scale in order to better illustrate the range of probability values smaller than 0.1, which is the range of interest in structural reliability problems.

Predicting the Complete Probability Distribution of Structural Response Using Subset Simulation with a Stochastic Ground Motion Model

The probability of exceeding a maximum inter-story drift ratio can also be calculated using an efficient simulation procedure such as Subset Simulation. Figure 5 illustrates (dashed line) this probability for a scenario earthquake of magnitude 7 and distance to site equal to 20 km that is calculated using the subset simulation procedure. The stochastic ground motion records generated by the simulation routine are constructed using the Atkinson and Silva (2000) stochastic ground motion model modified for a soil site. It should be noted that the uncertainty in the prediction of structural response in this case is described directly based on a complete probabilistic description of ground motion for a scenario earthquake and does not require the intensity measure as an intermediary variable. The number of non-linear dynamic analyses performed in this subset simulation procedure were equal to 1400 (this predicts the probabilities with a coefficient of variation around 30%). It can be observed from Figure 5 that, for the probability values smaller than around 0.5, the IM-based approach over-estimates the probability of exceeding maximum inter-story drift compared to the subset simulation result. However the median drift values (i.e., drift value corresponding to probability of exceedance equal to 0.50) predicted by the two alternative approaches are very close.

Predicting Structural Response Using IM and Stochastic Ground Motion Recordings

In order to better understand the observed differences between alternative ground motion representations on structural response prediction, the probability of exceeding various maximum inter-story drift ratios can be calculated by using records generated from the stochastic ground motion model in the IM-based method. The procedure for calculating the probability of exceeding a maximum inter-story drift is similar to the one described in the first category of response predictions. However, it is different in that it uses the synthetic attenuation relation (plotted in Figure 2) for predicting the intensity measure; and also that it uses a suite of synthetic records to predict the structural response given the intensity measure.

Figure 4 illustrates maximum inter-story drift angle values obtained by performing non-linear dynamic analyses on a suite of 20 synthetic ground motion records generated using the Atkinson and Silva ground motion model for a scenario earthquake of magnitude 7 and distance to site equal to 20 km. the parameters for Equation 2 in this case are given in Figure 4. It can be observed from the figure that spectral acceleration values are less scattered compared to the similar plot for the real ground motion records. This is consistent with the plots in Figure 2 where the range of probable spectral acceleration values for the synthetic records is narrower than that of the real records. Since spectral acceleration is the independent variable of the regression, the parameter estimations using linear regression are associated with more uncertainty compared to the real ground motion records. Later on, a way to improve the linear regression parameter predictions based on synthetic records is described.

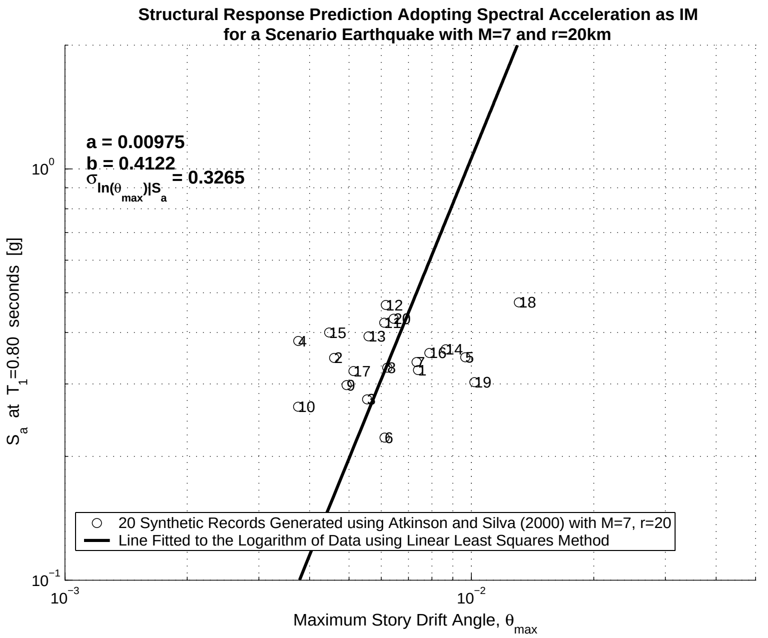

Figure 4- Structural Response (Maximum Inter-story Drift Angle) to a Suite of Synthetic Ground motion Records

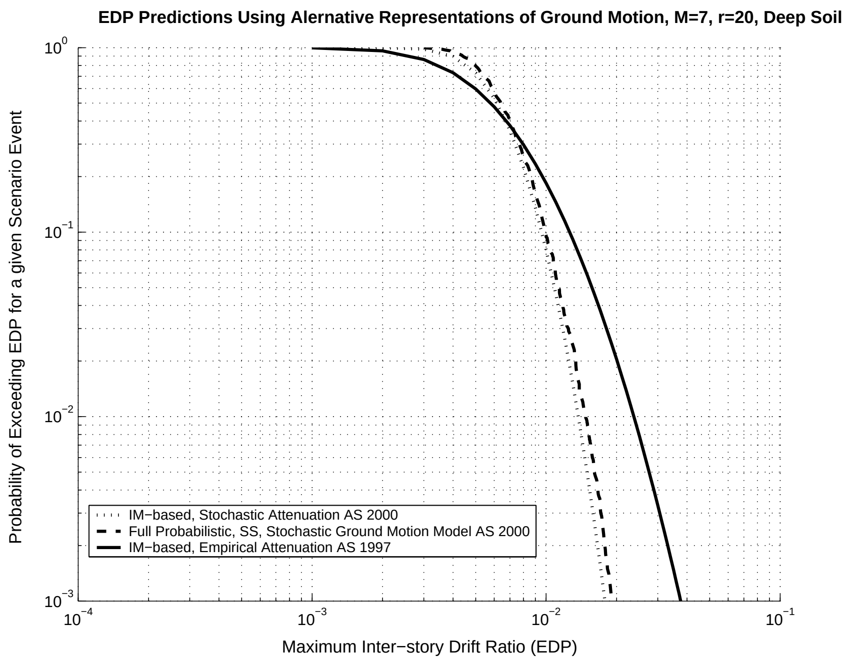

Figure 5- Effect of the Representation of Ground Motion Uncertainty on the Prediction of the Structural Response

The probability of exceeding a maximum inter-story drift (calculated by numerical integration as described in the first category), for the scenario earthquake of magnitude 7 and distance to site of 20 km, is plotted (in dotted line) in Figure 5. It can be observed that the result of the IM-based approach using synthetic records (dotted line) follows very closely the subset simulation result (dashed line). This is especially interesting since the IM-based approach can be devised with significantly less number of analyses compared to subset simulation. Since both approaches are based on synthetic records generated for the same scenario event, the good agreement observed between the results may be an indication of spectral acceleration being a suitable intensity measure in this case. However, as mentioned above, the small scatter in the spectral acceleration values in Figure 4 results in larger uncertainty associated with the estimation of the regression parameters compared to the regression parameter estimations in Figure 2 for the real ground motion records. Moreover, any judgment made with respect to the suitability of the spectral acceleration as an intensity measure (based on the synthetic ground motion records) is implicitly related to the suitability of the stochastic ground motion model for describing the future earthquakes occurring at the site.

Predicting Structural Response Using Synthetic Ground Motion Records Generated From a Bin
The differences observed in the predictions of structural response using real and synthetic recordings for a scenario earthquake in Figure 5 may in part be attributed to the differences between real ground motion selection and synthetic ground motion generation. Since the real ground motion records are chosen from a database of earthquakes that have taken place in the past, it is virtually impossible to select a suite of records with a specified large magnitude and a small distance. Therefore, real ground motions representing a scenario earthquake are chosen from a magnitude-distance bin covering a range of magnitude and distance close to those of the scenario event of interest. In contrast, the suite of synthetic records can be generated for a scenario earthquake with a specified magnitude and distance. In an attempt to emulate the selection of real ground motion records from a designated magnitude-distance bin, synthetic records are generated in this subsection from a bin of magnitude between 6.5 and 7.5 and closest distance between 10 km and 30 km (same bin definition as the real records). In order to generate such records, it has been assumed that the moment magnitude has a Gutenberg-Richter [4] probability distribution truncated on the two ends of the bin's magnitude interval. Also, it has been assumed that the earthquakes occur equal likely in a circular area confined between the two ends of the bin's distance interval [4]. It should be noted that in the IM-based approach, the synthetic records generated from a designated bin are only used in order to obtain the conditional probability distribution of maximum inter-story drift ration given spectral acceleration. Hence, the synthetic attenuation relation is still obtained for the specified magnitude and distance values. This is more consistent with the real attenuation relations that are provided as a function of magnitude and distance.

Figure 6 illustrates the spectral acceleration and maximum inter-story drift ratio pairs corresponding to 20 synthetic ground motion records generated as described above from a bin. The least squares line fitted to the data is also plotted in the figure. Comparing to Figure 4 where the synthetic records are generated for a scenario earthquake, the spectral acceleration values demonstrate larger variability similar to the real data case in Figure 3. This not only renders the regression parameter estimations with less uncertainty compared to the data in Figure 4 but it also makes the synthetic ground motion generation more similar to real ground motion selection. It should be noted that this exercise is not necessarily valuable from a practical point of view; it is rather an attempt to increase the common ground for drawing comparisons between structural response to real and synthetic ground motion records.

Figure 7 illustrates the probability of exceeding a maximum inter-story drift ratio obtained by following the alternative approaches described in this paper. This figure is the same as Figure 5 with regard to the alternative approaches used for calculating the probability of exceeding a maximum inter-story drift ratio. However, it differs from Figure 5 in that the synthetic records are generated from a magnitude-distance bin rather than with a specified magnitude and distance. Hence, the solid line corresponding to IM-based approach using real ground motion records is the same as Figure 5. It can be observed that the IM-based approach using synthetic records (the dotted line) follows more closely the solid line. Also the subset simulation results (the dashed line) demonstrates a better agreement with the solid line for smaller probability values, which is the range of interest in structural reliability problems. In summary, it can be observed that increasing magnitude-distance sampling interval results in comparatively wider probability distribution for the structural response, which seems to agree better with resulting probability distribution using real ground motion records.

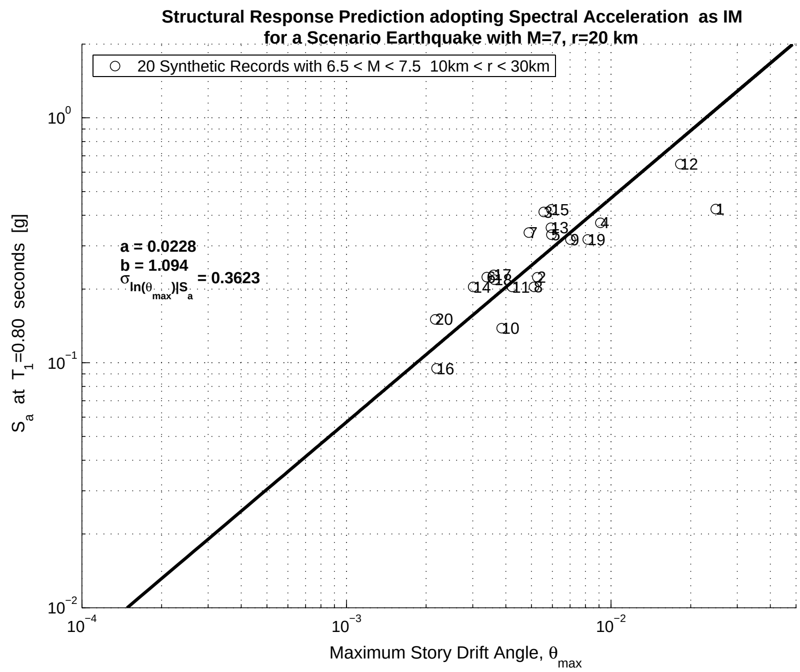

Figure 6- Structural Response (Maximum Inter-story Drift Angle) to a Suite of Synthetic Ground motion Records Generated from a Magnitude-Distance Bin Representing the Scenario Earthquake M=7 and r=20km.

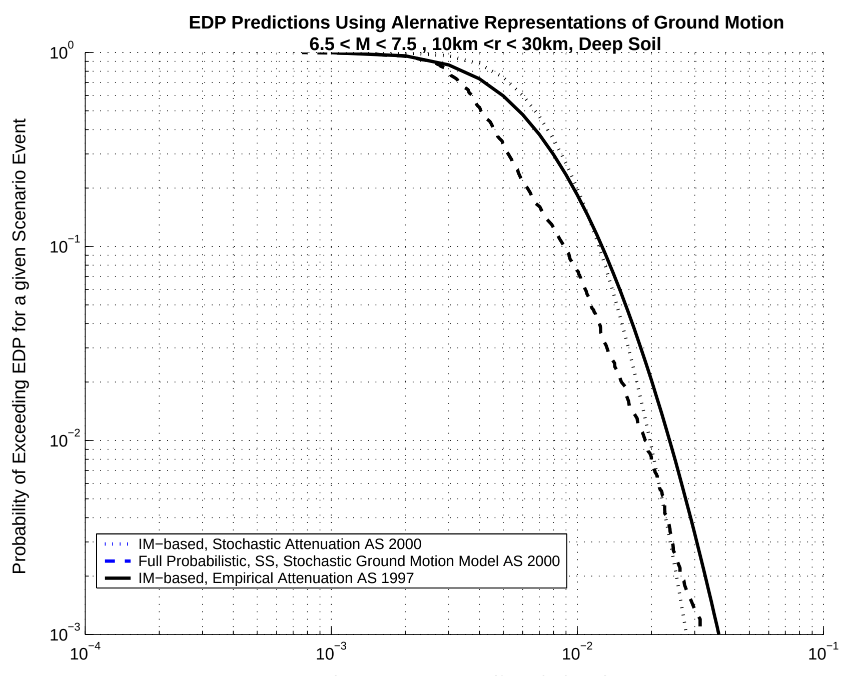

Figure 7- Effect of the Representation of Ground Motion Uncertainty on the Prediction of the Structural Response. The Synthetic Ground Motion Records are Generated from a Magnitude-Distance Bin Representing Scenario Earthquake with M=7 and r=20km

Observations

It can be observed from Figure 5 that the structural response predictions made using the IM-based approach and the synthetic ground motions are very close to those made using subset simulation and the stochastic ground motion model. This demonstrates that the efficient IM-based approach gives a good approximation to the probability distribution of maximum inter-story drift ratio. This result is especially interesting if one takes into account the number of simulations performed in the two methods, namely, 20 and 1400, respectively.

Figure 5 also demonstrates difference between the results obtained using real and synthetic records. It can be observed that the real and synthetic records provide roughly the same value for median maximum inter-story drift ratio. However, the probability distribution obtained using real records is more widely distributed compared to the probability distribution(s) obtained using synthetic records. The difference between probability distributions becomes more pronounced in the tail, i.e., small probability values. Apart from the differences between real and synthetic records, one may attribute the wider probability distribution obtained using real records to the fact that these records are selected from a magnitude-distance bin as opposed to having fixed magnitude and distance.

Figure 7 demonstrates the resulting probability distributions of maximum inter-story drift ratio using synthetic records when the records are generated from a bin defined in the same way as the real records. It can be observed that the probability distributions obtained using real and synthetic records show much better agreement compared to Figure 5.

The linear trend between the logarithm of maximum inter-story drift ratio versus the logarithm of spectral acceleration is more observable in Figure 6 when synthetic records are generated from a bin compared to Figure 4 where they are generated with fixed magnitude and distance. Since the variability is larger in the independent variable of the linear regression (in this case, spectral acceleration) in Figure 6, there is more confidence in the resulting parameter estimates.

SUMMARY AND CONCLUSIONS

The effect of alternative ground motion uncertainty representations on the prediction of structural response for a scenario earthquake event is compared. The uncertainty in the ground motion can be described by a complete probability distribution based on a stochastic ground motion model. Alternatively, an intermediary variable (or vector of variables) known as the intensity measure can be adopted to describe the uncertainty in the ground motion. Response predictions based on the complete probabilistic model of the ground motion are made using an efficient simulation technique known as Subset Simulation. The effect of ground motion representation on the prediction of the intensity measure itself for a scenario event has also been compared. This is equivalent to comparing the adopted empirical attenuation relation to the synthetic attenuation relation constructed by applying subset simulation to a linear oscillator subjected to the synthetic ground motion records. Benchmarking response predictions based on the two alternative representations of ground motion uncertainty is also useful in that it provides a criterion for judging and comparing how effective a candidate intensity measure is. This is especially useful in the selection of the most desirable intensity measure for representing the uncertainty in the ground motion.

It has been observed that the response predictions provided by the two alternative representations of ground motion uncertainty are very close when they both use stochastic ground motions. However, the parameter estimates provided by linear regression in the IM-based approach using synthetic ground motions have larger uncertainty associated with them compared to when real ground motions are used. Therefore, the sensitivity of response predictions to the linear regressions parameters using stochastic ground motions needs to be studied. The response predictions using real ground motion records (IM-based approach) and those provided using synthetic ground motion records (IM-based approach and subset simulation) agree on the estimated median maximum inter-story drift ratio (i.e., value corresponding to probability of exceedance equal to 0.50). However, the predictions are significantly different for small probability values. The shape of the probability distribution of response obtained using real records is wider compared to those predicted using synthetic records. This can be in part attributed to the difference between synthetic record generation and real ground motion selection. Being limited to the database of recorded ground motions, it is difficult to select a suite of ground motions with specified large magnitude and small distance. Therefore, these records are selected from a magnitude-distance bin that is constructed within designated intervals around magnitude and distance of the scenario earthquake. In contrast, magnitude and distance are fixed for the synthetic records generated for a scenario earthquake. This can lead to less variability in spectral acceleration values and hence in structural response in the case of synthetic records as compared to real records. It would have been more desirable to be able to select real records with the specified magnitude and distance and to compare the resulting structural response prediction to those using synthetic records. However, in lieu of creating such selection, synthetic ground motion records are generated in a manner that mimics real ground motion selection from a bin of records. The response predictions obtained using the new set of synthetic ground motion show better agreement with response prediction using real records.

The next logical step will be to benchmark the structural response predictions, obtained by the alternative approaches described in this paper, considering all the possible earthquake scenarios at the site. It is also extremely important to ensure that the stochastic ground motion model is able to predict the ground motions expected to occur at the site. Therefore, the future comparisons need to include alternative stochastic ground motion models. Finally, the benchmarking of the alternative representations of ground motion uncertainty needs to be performed with respect to variables defining the performance objectives, such as expected repair cost in the structure.

ACKNOWLEDGEMENT

This work was supported in part 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). This support is gratefully acknowledged. 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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