# Application of the Subset Simulation Method in Predicting the Seismic Response of an Existing RC Frame Structure

F. Jalayer, J.L. Beck, K. A. Porter & J.F. Hall
*California Institute of Technology*

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ABSTRACT: An advanced simulation scheme known as the subset simulation can be used to efficiently compute the probabilities of rare events, such as the seismic risk for a structural system. The seismic risk assessment of a structure may be significantly affected by the representation of ground motion uncertainty. A direct probabilistic presentation of ground motion for a given scenario earthquake can be constructed by generating ground motions based on a stochastic model that depends on seismic source parameters. The uncertainties in magnitude and distance can be accounted for by simulating ground motions from a joint probability distribution that is constructed based on the potential of the surrounding faults producing a specified scenario earthquake. This paper employs the subset simulation technique in order to generate ground motions capable of inducing structural response that falls into nested failure regions; the intersection of which, defines a designated structural response threshold. Alternatively, the ground motion uncertainty can be represented by adopting parameters known as the intensity measures (IM), and using attenuation relationships in order to relate the IM to seismic source parameters. The uncertainty in the response of an existing reinforced concrete frame structure in Los Angeles is obtained by following the alternative approaches described above. This structure is known to have suffered shear failure in its columns during the 1994 Northridge earthquake.

## 1 INTRODUCTION

Being events with extreme consequences, earthquakes are amongst the most significant input to a structural system. The small frequency and the large uncertainty associated with their occurrence, renders earthquakes also one of the most difficult structural input categories to predict. There are alternative ways to represent the uncertainty in the prediction of earthquakes in the structural performance assessments.

One way to represent the uncertainty in the ground motion is by adopting a parameter (or a vector of parameters) known as the intensity measure (IM). Structural performance assessment based on this representation can be broken down into two stages, namely, the structure-specific stage including performance assessment for a given value of the intensity measure, and the site-specific stage including estimation of the likelihood that an earthquake with a given value of intensity measure takes place. This two-stage break-down facilitates incorporating common structural analysis procedures and seismic hazard analysis procedures in a more-or-less uncoupled manner. However, ensuring that the adopted IM is describing thoroughly the ground motion characteristics is not only crucial but also a non-trivial task.

Alternatively, structural performance assessment can be based directly on a probabilistic description of ground motion. A direct probabilistic presentation of ground motion for a given scenario earthquake (e.g., defined by a specific magnitude and source-to-site distance) can be constructed by employing a stochastic ground motion procedure in order to generate (synthetic) ground motions. The uncertainties in magnitude and source-to-site distance can be accounted for by simulating ground motions from a joint probability distribution, constructed based on the potential of the surrounding faults in producing different earthquake scenarios.

The direct probabilistic representation of the ground motion can be incorporated by a simulation scheme in order to predict the structural response.

Subset simulation technique (Au and Beck 2001 and 2003) is an advanced simulation scheme that can predict the structural response more efficiently than standard Monte Carlo simulation.

The effect of the alternative representations of ground motion uncertainty on the structural response was investigated by the authors in an earlier paper (Jalayer et. al. 2004) for a given magnitude and distance. It was concluded that the direct probabilistic representation needed to be enhanced by taking into account the uncertainties in the parameters of the stochastic ground motion generation procedure. This paper extends the scope of the investigation by taking into account the potential of the surrounding faults in producing a range of possible magnitude and distance scenarios, based on the results of site-specific probabilistic seismic hazard analysis. Furthermore, the overall effect of the uncertainty in the stochastic ground motion model parameters is being considered.

## 2 METHODOLOGY

This section lays out a summary of the methodology used for estimating the probability of exceeding a specified structural response parameter by following the two alternative approaches described in the introduction.

### 2.1 *Subset Simulation: An Efficient Simulation Technique*

Subset simulation (Au and Beck, 2001, 2003) 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. A Markov Chain Monte Carlo Simulation (MCMC) technique is employed in order to generate samples based on the conditional probability distribution(s) for the uncertain parameters given that a particular failure threshold is surpassed.

This paper employs the subset simulation technique in order to generate ground motion records capable of inducing structural response falling into nested failure regions; the intersection of which, defines a designated structural response threshold. A direct probabilistic description of ground motion uncertainty can be constructed based on the ground motion records generated using the subset simulation technique. The procedure for generating the ground motions and the application of subset simulation in estimating the structural response parameter based on a direct probabilistic description of ground motion uncertainty is going to be described in more detail in the next sections.

### 2.2 *Stochastic Ground Motion Generation*

One of the procedures commonly used for generating synthetic ground motion records is referred to as the *stochastic ground motion modeling* (Boore, 1983). This procedure consists of generating a time sequence of independent Normally distributed uncertain variables with zero mean and a variance chosen so that the time sequence has (on average) unit Fourier amplitude spectrum. This time sequence is multiplied by an envelope function in order to model the finite duration of a ground motion record. The Fourier amplitude spectrum of the enveloped time sequence is multiplied by an amplitude spectrum that describes the ground motion amplitude over a range of frequencies as a function of ground motion source parameters. The amplitude spectrum, which has an effect similar to a high-cut filter, is normally based on a simple physical model of earthquake dislocation modified in order to take into account the effect of finite fault dimensions and to remove frequencies higher than a certain cut off frequency. Finally, the filtered Fourier amplitude spectrum is transformed back into the time domain.

### 2.3 *Direct Probabilistic Representation of Ground Motion using Subset Simulation and Stochastic Ground motion Modeling*

Subset simulation procedure is shown to be robust with respect to the number of uncertain parameters in the problem well as to the type of the structural system and the type of loading (Au and Beck, 2003). Due to its robustness with respect to the type of the structure and loading, subset simulation procedure can be applied in estimating response parameters for non-linear structures subjected to seismic ground motions. Moreover, due to its robustness with respect to the number of uncertain parameters, this simulation scheme can be used in conjunction with the stochastic ground motion generation in order to construct a direct probabilistic representation of the ground motion by taking into account the uncertainties in ground motion parameters such as, input phase, stress drop, magnitude, focal depth and source-to-site distance. Besides, it can take into account the modeling uncertainty in ground motion prediction (Toro et al., 1997); for instance, the uncertainty in the (mean) amplitude spectrum used in generating the synthetic ground motions.

As mentioned in the previous section, subset simulation technique is an advanced simulation tool for efficiently computing small “failure probabilities”, where failure probability can be defined as the probability of exceeding a certain value of the structure response parameter of choice. This paper demonstrates the application of subset simulation in estimating two alternative structural response parameters.

### 2.3.1 *Applying Subset Simulation in order to calculate Spectral Acceleration Hazard*

As the first structural response parameter, the spectral acceleration at the fundamental period of structure, which is defined as a linear function of the maximum displacement response of a single-degree of freedom (SDOF) linear oscillator with a natural frequency equal to the fundamental period of the structure, to a seismic ground motion record, is selected. This parameter, which is denoted by, $S_a(T_1)$ or more simply by, $S_a$, will be referred to as the spectral acceleration at the fundamental period or more briefly as the spectral acceleration. Subset Simulation can be applied to a linear SDOF oscillator in order to calculate the mean annual rate of exceeding different values of the spectral acceleration, a quantity that is more commonly known as the spectral acceleration hazard.

### 2.3.2 *Applying Subset Simulation in order to calculate a displacement-based non-linear structural response parameter*

Alternatively, subset simulation can be applied in order to estimate non-linear structural response parameters. As the second parameter of choice, this paper focuses on maximum inter-story drift angle, which is the maximum differential displacement between two adjacent stories over the height of the structure and over the time history of the ground motion. Maximum inter-story drift angle is a particularly well-studied structural response parameter not only because it is a global response measure but also because it is related to the joint rotation in the columns at each story, which is a comparatively more local response measure. Maximum inter-story drift angle or more briefly *drift* is denoted by $\theta_{\max}$. Subset simulation can be applied to calculate the mean annual rate of exceeding maximum inter-story drift angle, also referred to as the *drift hazard*, for a frame structure.

### 2.3.3 *Sources of ground motion uncertainty*

As mentioned before, subset simulation is particularly suitable for high-dimensional problems, meaning problems with a large number of uncertain parameters. It also allows for grouping the uncertain parameters according to their probability distribution and to the manner in which the structural response parameter is going to be affected by them (Au and Beck, 2003). The uncertain parameters considered in this paper can be divided into two groups, namely, (a) large number of independent identically-distributed (i.i.d.) uncertain variables and (b) small number of influential uncertain parameters. The input time sequence, used as a seed in stochastic ground motion generation procedure, belongs to the first group. Moment magnitude, source-to-site distance, and modeling uncertainty belong to the second category. The modeling uncertainty describes the uncertainty in estimating the (mean) amplitude spectrum of the ground motions for a given magnitude and distance. Although it does not have a particular physical interpretation, it reflects the overall effect of the insufficient state of knowledge about ground motion parameters that affect the (mean) amplitude spectrum for a given magnitude and distance.

## 2.4 *(Indirect) Probabilistic Representation of Ground Motion using the Ground Motion Intensity Measure (IM)*

The uncertainty in the ground motion can also be described by adopting a parameter (or a vector of parameters) known as the intensity measure (IM) in order to describe the ground motion characteristics (Luco and Cornell, 1998, Jalayer and Cornell 2003). The probability of exceeding a given value of the adopted IM can be calculated based on the results of probabilistic seismic hazard analysis (Cornell, 1968). For a given value of the adopted IM, a suite of real ground motion recordings is selected and applied to the structural model. The structural response to the suite of ground motion records can be employed in order to obtain a conditional probability distribution for the structural response at a given level of the IM. Finally, the probability of exceeding the structural response parameter of interest can be calculated by integrating the conditional probability of exceeding the structural response at a given level of IM multiplied by the likelihood of an event with intensity equal to the given level of IM occurring for all possible values of the ground motion intensity.

### 2.4.1 *Probabilistic Seismic Hazard Analysis*

Developed originally in 1968 by C. A. Cornell, probabilistic seismic hazard analysis evaluates the probability that a given level of ground motion intensity is exceeded at the site of an engineering project by incorporating the influence of all potential sources of earthquakes and the average activity rates assigned to them. This is done by calculating (and integrating) the probability of exceeding a given level of ground motion intensity for all the possible earthquake scenarios, usually represented by their magnitude and distance to the site. Modern probabilistic seismic hazard analysis is built directly on the basic approach developed by Cornell; it differs mostly in that it also incorporates uncertainty in the estimation of the median ground motion intensity for a given magnitude and distance (i.e., the attenuation relation).

### 2.4.2 *Probabilistic Seismic Hazard De-aggregation*

Seismic hazard de-aggregation (Bazzurro and Cornell, 1998) consists of finding the conditional probability of magnitude and distance pairs occurring given that a certain level of ground motion intensity is being exceeded. The can be done by re-arranging the data used in probabilistic seismic hazard analysis. Hazard de-aggregation provides an insight into the relative contribution of different magnitude and source-to-site distance pairs to the probability of exceeding a given level of ground motion intensity.

This paper employs the de-aggregation of seismic hazard at different levels of ground motion intensity in order to estimate a joint probability distribution for magnitude and distance. This joint probability distribution, which reflects the potential of the surrounding faults in producing a specified scenario earthquake, will be used as the sampling distribution for magnitude and distance in the subset simulation scheme. The objective is to provide a common ground for comparing the direct probabilistic description of ground motion uncertainty with the indirect representation based the results of PSHA for the adopted intensity measure.

## 3 NUMERICAL EXAMPLE

The methodology described in the previous section is applied to an existing reinforced concrete frame in order to estimate the structural response using alternative representations of ground motion uncertainty.

### 3.1 *Model Structure: Transverse Frame of an Existing Building*

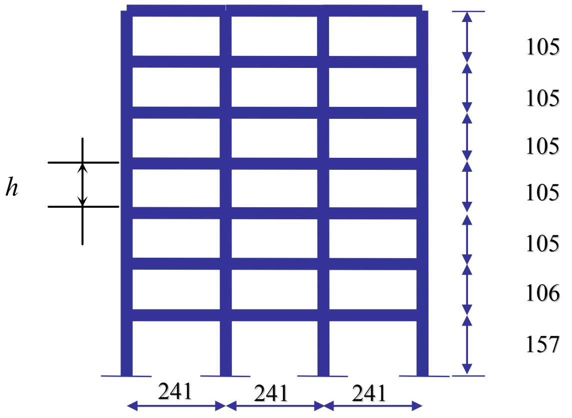

Figure 1: Model structure is a transverse frame in an existing RC moment-resisting structure (dimensions are in inches).

One of the transverse frames in a hotel structure located in Van Nuys is selected as the structural model (Figure 1). This building is an older reinforced concrete (RC) structure that has 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 et al., 1999). The structural model takes into account stiffness and strength degrading behavior in the nonlinear range for both flexure and shear (see Jalayer, 2003 for more details).

### 3.2 *Atkinson and Silva (2000) Fourier Amplitude Spectrum*

The stochastic ground motion procedure can be employed for generating samples of synthetic ground motion records to be incorporated in the subset simulation scheme. In this paper, the stochastic ground motion generation procedure is based on the amplitude spectrum proposed by Atkinson and Silva (2000) at a given magnitude and distance. The Atkinson and Silva (2000) model is two-corner frequency point-source model, which is based on a physical model of earthquake dislocation due to the propagation of shear waves that was developed by Brune (1970). It is modified from the original form in order to take into account the effect of the finite rupture length.

As mentioned before, the Fourier amplitude spectrum of the synthetic records, generated by the stochastic ground motion method, matches on average with the amplitude spectrum proposed by Atkinson and Silva (2000). The average Fourier amplitude for a sample of 50 synthetic ground motion records (jagged line) and Atkinson and Silva (2000) spectrum (solid line) are plotted in Figure 2.

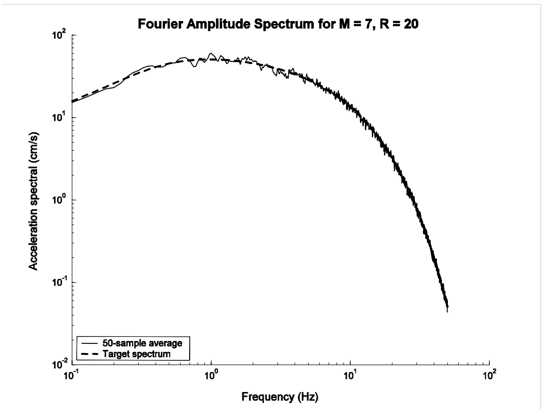

Figure 2: Atkinson and Silva (2000) (Mean) Fourier Amplitude Spectrum

### 3.3 *Uncertainty in the Parameters*

As mentioned in Section 2.3.3, the uncertain parameters within the subset simulation scheme can be arranged into groups based on their probability density function (PDF) and on how they affect the structural response parameter. The uncertain ground motion parameters have been divided into two groups. The first group consists of large number of independent and identically-distributed (i.i.d.) uncertain variables that affect the probability of failure (as defined in Sections 2.3.1 and 2.3.2) as a whole and the second group consists of small number of influential uncertain variables that may affect the probability of failure individually. It should be noted that the grouping of uncertain parameters allows for taking into account possible correlations between the uncertain parameters within a group.

### 3.3.1 *Group 1: Large number of (i.i.d.) uncertain parameters*

As it was mentioned in Section 2.2, the stochastic ground motion generation procedure employs a time sequence of uncertain parameters, also referred to as *input phase*, as a seed for making synthetic ground motion. It is assumed that this time sequence is consisted of an array of i.i.d. uncertain parameters described by Normal distribution with zero mean and variance chosen so that the Fourier amplitude spectrum of the input time sequence is equal to unity (on average).

### 3.3.2 *Group 2: Small number of influential uncertain parameters*

The subset simulation procedure takes into account the uncertainty in moment magnitude, source-to-site distance, and (mean) Fourier amplitude spectrum. For the sake of simplicity, it is assumed that the uncertainty in the Fourier amplitude spectrum does not depend on magnitude and distance, although scientific evidence suggests otherwise (Toro et al., 1997). The uncertainty in magnitude and distance is described by a joint PDF that is extracted from the results of site-specific probabilistic seismic hazard analysis. The following subsections outline in more detail the probabilistic description of the uncertain parameters.

#### *(1) Uncertainty in Fourier amplitude spectrum*

The uncertainty in Fourier amplitude spectrum is described by a lognormal probability density function with median equal to the (mean) amplitude spectrum proposed by Atkinson and Silva (2000) and standard deviation of the logarithm equal to 0.45. This value is chosen so that the hazard curve for spectral acceleration at fundamental period of the structure ($T_1 = 0.85 \sec$) obtained using subset simulation matches (roughly) that obtained from PSHA. As mentioned before, this parameter does not have a specific physical interpretation, it reflects the overall effect of the uncertainty in ground motion parameters such as, focal depth, stress drop, anelastic attenuation, and the uncertainty in the ground motion model proposed by Atkinson and Silva (2000) for a given magnitude and distance.

#### *(2) Uncertainty in magnitude and distance*

The joint probability density function (PDF) for magnitude and distance is derived based on the results of the de-aggregation of spectral acceleration hazard, which have been produced using a software for probabilistic seismic hazard analysis (HAZ30) developed by Abrahamson (2001). Figure 3 illustrates the joint PDF for magnitude and distance. It should be noted that the joint PDF shown in the figure provides the probabilistic description of magnitude and distance given that an earthquake event of interest (e.g., $M \ge m_0$) occurs somewhere along one of the faults surrounding the site. Here, the event of interest is defined as an earthquake with a magnitude greater than or equal to $m_0 = 5$.

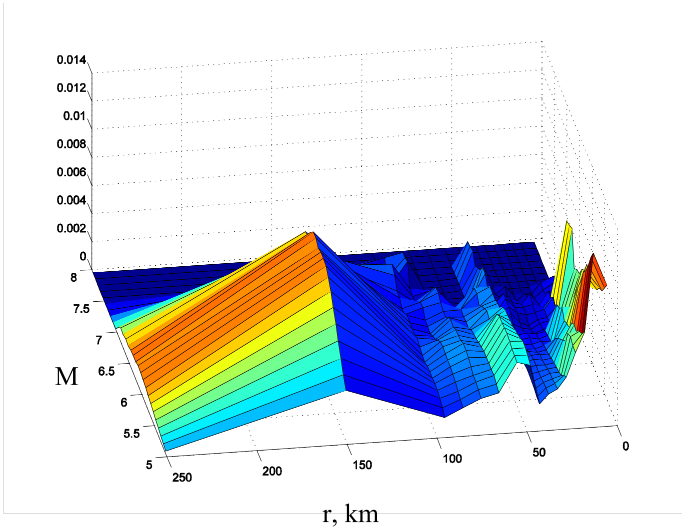

Figure 3: Joint probability density function for magnitude and distance based on the results of the de-aggregation of seismic hazard

The shape of the distribution reflects the position of the faults surrounding the site. It can be observed that the PDF is smoother at large distances; this is due to the coarser definition of de-aggregation distance bins at larger distances. It was presumed that large-magnitude earthquakes occurring at a small distance from the site are going to have the most significant contribution to causing extreme behavior in the structure. However, the two peaks observed at distances equal to 50 km and 150 km are probably reflecting the effect of the two large segments of San Andreas Fault, namely, Mohave and Cholame-Carrizo. The absolute peak of the distribution happens at distances less than 10km, where the faults of the Los Angeles region are concentrated.

## 3.4 *Estimation of Spectral Acceleration Hazard*

Subset simulation can be employed to calculate the probability of failure, defined as exceeding specific values of spectral acceleration. As mentioned before in Section 2.3.1, spectral acceleration is calculated by obtaining the maximum displacement response of a SDOF linear oscillator to a ground motion record time history.

Subset simulation is performed at 6 nested failure levels at which, the conditional probability of failure is constant and is equal to $0.10$. The total probability of failure, which is equal to the product of the conditional failure probabilities at all levels, is equal to

$10^{-6}$. The first level of the subset simulation procedure is in fact a standard Monte Carlo (MC) simulation with 500 samples. Since the conditional probability of failure at each level is fixed and equal to $0.10$, the spectral acceleration value that is being exceeded by ten percent of the samples (i.e., 50 samples) defines the onset of the first failure level. The 50 samples that define the failure region are being used as "seeds" in the second (next) level of the subset simulation (see Au and Beck, 2003). The second (next) level of the subset simulation procedure employs the Markov Chain Monte Carlo (MCMC) simulation in order to generate samples using the using the "seeds" from the first (previous) level. Each seed is used to generate a Markov chain of 10 samples; this generates a total of 500 samples in the second (next) level. The onset of failure at the second level is marked (same as in the first level) by finding the spectral acceleration value that is being exceeded by ten percents of the samples in that level. Subset simulation continues as long as either a specific probability of failure or spectral acceleration value is reached.

The probability of failure calculated using subset simulation is given that an earthquake event of interest occurs somewhere along a surrounding fault; event of interest being defined as earthquakes of magnitude greater than $m_0 = 5$ (see section 3.2.2). Assuming that the mean annual rate of exceeding magnitude five earthquakes in Southern California is equal to $0.60$, the mean annual rate of exceeding a particular spectral acceleration level in one year can be calculated by multiplying the probability of exceeding this level by $0.60$. This provides the mean annual rate of exceeding spectral acceleration or spectral acceleration hazard curve; which is plotted in Figure 4 (dashed line).

Alternatively, the spectral acceleration hazard curve can be calculated by adopting the spectral acceleration at the fundamental period of the structure as the ground motion intensity measure (IM) and performing probabilistic seismic hazard analysis (PSHA) procedure specific to the site of the structure. This is done by employing software developed by Abrahamson (2001); in which, the spectral acceleration for a given magnitude and distance was predicted from the empirical ground motion relations (also known as, *empirical attenuation relations*) developed by Abrahamson and Silva for shallow crustal earthquakes on firm soil (Abrahamson and Silva, 1997). The resulting hazard curve is also plotted in Figure 4 (solid line).

It can be observed from the figure that the spectral acceleration hazard curve calculated directly using subset simulation shows good agreement with the one calculated by adopting $S_a(T_1)$ as the intensity measure and using PSHA. However, it should be reminded that, in applying the subset simulation technique, the uncertainty in the (mean) Fourier amplitude spectrum was adjusted so that the resulting spectral acceleration hazard agrees well with the one obtained by using PSHA (see section 3.2.2). This emphasizes the importance of accounting for various sources of uncertainty when applying simulation techniques for response assessments.

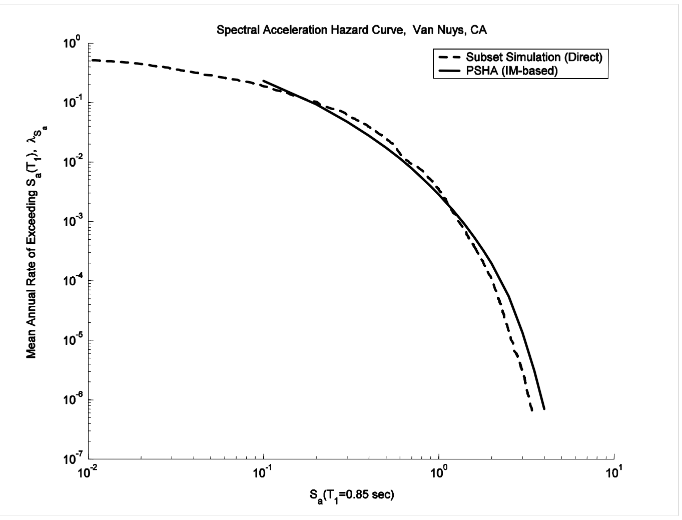

Figure 4: Spectral Acceleration Hazard Curve

In order to calculate spectral acceleration hazard values as small as $10^{-6}$ using standard Monte Carlo simulation, one needs to perform at least $N \succ 10^6$ analyses; this is while subset simulation has been carried out by performing only $N = 500 + 5 \times (500 - 50) = 2750$ analyses. This demonstrates the efficiency of the subset simulation technique for calculating very small probabilities.

### 3.5 *Estimation of Structural Response*

Subset simulation procedure can also be used to calculate the probability of exceeding specific values of a non-linear displacement-based structural response parameter. As it was mentioned in Section 2.3.2, maximum inter-story drift angle, denoted by $\theta_{\max}$, is chosen as the structural response parameter. Hence, subset simulation technique is used in order to calculate the probability that maximum inter-story drift angle response of the model structure (illustrated in Figure 1) exceeds certain values. The same as when calculating the spectral acceleration hazard, the conditional probability of failure at each level is fixed and equal to $0.10$. Subset simulation is performed at three levels; hence, the total probability of failure is equal to, $0.001$. The procedure for finding the failure regions at each level is similar to that explained in Section 3.4 for calculating the spectral acceleration hazard. At each level, 1000 simulations were performed. The mean annual probability of exceeding maximum inter-story drift angle is plotted in Figure 5 (dashed line).

Alternatively, the mean annual rate of exceeding maximum inter-story drift angle can be calculated (indirectly) by adopting the spectral acceleration at the fundamental period of the structure as the intensity measure. In this approach, a suite of 30 real ground motion records have been selected from a catalog of California ground motion recordings on stiff soil from a magnitude range of $5.5 \le M \le 7.5$ and source-to-site distances of $15 \le r \le 120$ km. A non-linear dynamic analysis procedure entitled the *Multiple-Stripe Analysis* (Jalayer 2003) is employed in order to obtain a (conditional) probabilistic description for drift angle at different spectral acceleration levels. The conditional probability of exceeding a given value of $\theta_{\max}$ at each spectral acceleration level, $S_a = x$, is multiplied by the mean annual rate of occurrence for an event with $S_a = x$ (based on PSHA results) and integrated over the range of possible spectral acceleration levels. This procedure is repeated in order to calculate the mean annual rate of exceeding maximum inter-story drift angle $\theta_{\max}$ for a range of $\theta_{\max}$ values and the resulting curve is plotted in Figure 5 (solid line). The IM-based approach for calculating the mean annual rate of exceeding drift, which employs non-linear dynamic analysis procedures and is based on the results of probabilistic seismic hazard analysis, is described in detail in Jalayer (2003).

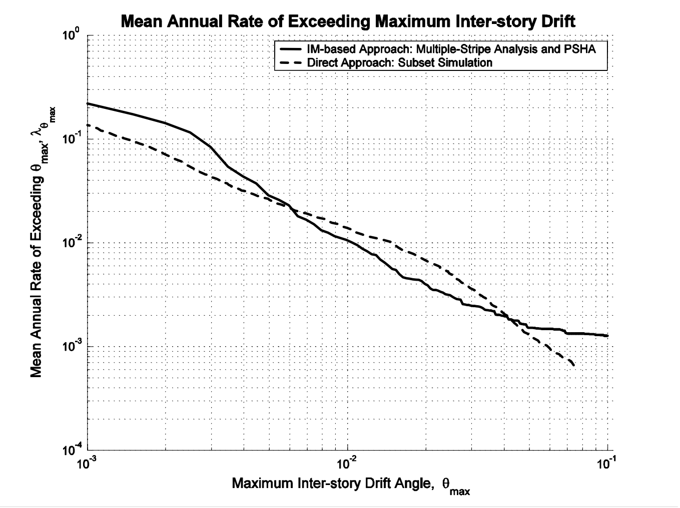

Figure 5: Mean Annual Rate of Exceeding Maximum Inter-story Drift Angle

The difference observed between the two curves in Figure 5 may be (partly) due to the choice of spectral acceleration as the ground motion intensity measure. It can also be due to the difference between how the real ground motion recordings and the synthetic ones affect the maximum inter-story drift response of the non-linear model structure. The section on future research (Section 4) will outline future plans for further investigating the causes of the difference observed between the structural response estimates obtained by following the two alternative approaches.

### 3.5.1 *Sampling of Magnitude-Distance Pairs in the Subset Simulation Procedure*

It is interesting to gain an insight into how the subset simulation procedure is sampling the magnitude-distance pairs so that the resulting synthetic ground motions are able to push the structure into the failure region. The magnitude-distance pairs that are sampled in the first and third (last) level of the Subset Simulation are plotted in Figure 6. The small and thin circles illustrate the $(M,r)$ pairs sampled at the first simulation level and the large and thick circles illustrate the $(M,r)$ pairs sampled at the third (final) simulation level. The contours of the joint probability density function (PDF) for magnitude and distance are also plotted in the figure (solid lines).

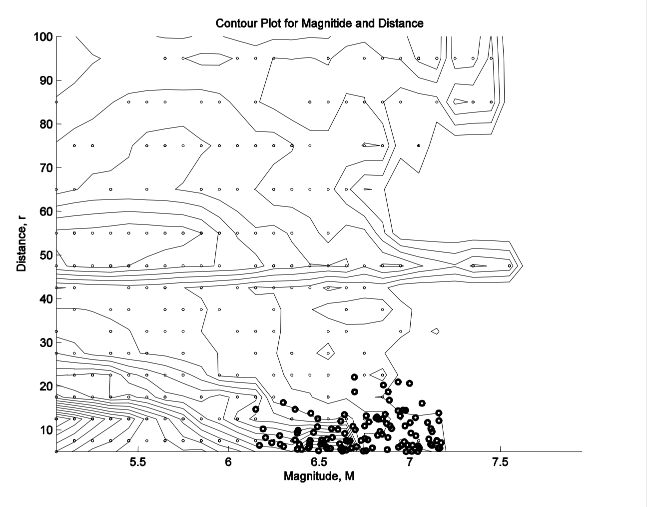

Figure 6: Contour Plot of Probability Density Function for Magnitude and Distance and the Simulated $(M,r)$ Pairs

In the first simulation level, the $(M,r)$ samples seem to follow the contours of the joint probability density function. This is expected because the first level of the subset simulation procedure is in fact a standard Monte Carlo simulation. However, in the last simulation level, the $(M,r)$ pairs are sampled so that they are concentrated in the large-magnitude small-distance corner of the PDF. This suggests that, in order to be able to "push" the structure into the failure region, the subset simulation procedure is sampling magnitude and distance from a region of the joint PDF that affects the structural response in the most severe manner.

## 4 CONCLUSIONS AND FUTURE WORK

Subset simulation is an advanced simulation technique that can be used to efficiently compute the probabilities of rare events such as severe earthquake damage in the structure, based on a direct probabilistic representation of seismic ground motion. Alternatively, these probabilities can be estimated indirectly by adopting a parameter known as the ground motion intensity measure in order to represent the ground motion and selecting a suite of real ground motion in order to estimate the structural response for a given level of the ground motion intensity measure. This paper strives to both demonstrate the efficiency of subset simulation in computing small failure probabilities and also to compare the structural response assessments provided by subset simulation using synthetic ground motion records with those obtained by adopting an intensity measure and using real ground motion records.

The subset simulation procedure employed in this paper takes into account the uncertainty in magnitude and distance, synthetic ground motion input phase and the mean Fourier amplitude spectrum of the synthetic ground motions.

Subset simulation was performed in two parts. In the first part, the mean annual rate of exceeding spectral acceleration at the fundamental period of the structure (i.e., spectral acceleration hazard) was calculated. The uncertainty in the Fourier amplitude spectrum was chosen so that the resulting spectral acceleration hazard was in agreement with the one calculated using probabilistic seismic hazard analysis. Since the annual rate of exceeding large spectral acceleration values was very small (of the order of $10^{-6}$), subset simulation provided an efficient way of calculating the spectral acceleration hazard. In the second part, subset simulation was used to calculate the mean annual rate of exceeding maximum interstory drift angle in the model structure. The results were compared with those obtained indirectly by employing a non-linear dynamic procedure known as Multiple-Stripe Analysis and based on the results of PSHA at the site. The difference observed between the results may be attributed to the choice of an intensity measurer in order to represent the ground motion characteristics in the indirect approach and also to the difference between how real and synthetic records may affect the structural response.

As the future direction, the authors intend to employ intensity measures other than spectral acceleration in the IM-based approach and compare with the direct probabilistic approach using subset simulation. They also intend to take into account explicitly the uncertainty in the ground motion modeling and parameters.

## 5 ACKNOWLEDGEMENTS

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