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OPTIMIZATION OF RESPONSE SIMULATION FOR LOSS ESTIMATION USING PEER'S METHODOLOGY

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SUMMARY

A study is performed on the number of response history analyses (RHA) required to capture the median, the standard deviation of natural log, and the mean annual frequency of exceedance of the structural response parameters. Two types of structural responses are investigated; interstory drift ratio, *IDR*, and the peak floor acceleration, *PFA*. These two responses are essential for loss estimation of structural and non-structural components in buildings. Recommendations are made on the size of the required number of RHA to capture each of the above probability parameters at different levels of deformation.

INTRODUCTION

The goal in Performance-Based Earthquake Engineering (PBEE) is to evaluate the performance of a structure in terms of quantitative measures of seismic performance. Different measures of seismic performance can be selected in a PBEE framework. A few examples are direct economic losses, downtime of the facility, and the fatality rate in the building.

The Pacific Earthquake Engineering Research (PEER) center has developed a probabilistic platform to quantitatively measure the performance in different types of structures. A great advantage of the created platform in PEER is its transparency in identifying and modeling different sources of uncertainty that can affect the target performance measure.

On the basis of PEER's platform a methodology is developed to estimate economic losses in specific buildings, Miranda [1]. The methodology takes into account different sources of uncertainty that contribute to the economic losses in buildings, namely uncertainty at the response level, uncertainty at the damage level and uncertainty at the repair cost level. Furthermore, the methodology takes into account the effects of correlation between loss in individual components on the total economic loss of the building, Aslani [2].

A primary step in the estimation of economic losses in buildings produced from earthquake events is a probabilistic evaluation of the structural response at increasing levels of ground motion intensity.

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Researchers have used different approaches to estimate the probability parameters of structural response in different facilities. One approach that carefully accounts for the variation of the response parameters at different earthquake scenarios is described in Miranda and Aslani [1].

The number of response history analyses, RHA, in a probabilistic structural response analysis has a significant effect on the runtime and practicality of the procedure. Different researchers have used various numbers of RHA in their studies. Luco [3] used a set of 59 earthquake ground motion time histories for their study. Alavi [4] used 40 ground motion time histories in their study.

Our investigations show that the question of "How many response history analyses is enough in probabilistic response analysis?" could be answered by carefully breaking the problem into the main factors that can contribute to the problem. These factors are: the selected intensity measure in the analysis, the level of deformation, the selected structural response parameter, and the probability parameter of interest for that structural response.

Presented in this study is an investigation on the number of RHA required in a probabilistic response assessment. First, we present a summary of probabilistic response assessment procedure in buildings. In the next step, we describe a generic procedure that is used to optimize the number of response simulation for different types of response parameters. The procedure is then applied to three different probability parameters of the interstory drift ratio, *IDR*, and peak floor acceleration, *PFA*, in a building. The effects of the level of deformation and type of the structural response on the required number of RHA are investigated for different probability parameters of the response.

PROBABILISTIC SEISMIC RESPONSE ASSESSMENT IN BUILDINGS

The mean annual frequency (MAF) of exceeding a certain level of response in a building can be computed as

$$\nu(EDP > edp) = \int_0^{\infty} P\left[EDP \mid IM\right] \left| d\nu(IM) \right| \quad (1)$$

where $d\nu(IM)$ is the derivative of the seismic hazard at the site, and $P\left[EDP \mid IM\right]$ is the probability of the structural response exceeding a certain limit for a given earthquake scenario, *IM*.

Each term in the right-hand side of Eq. (1) is evaluated using a probabilistic analysis approach. The seismic hazard at the site is estimated through a probabilistic seismic hazard analysis (PSHA). PSHA is a rational approach to account for different sources of uncertainty of the ground motion. Two sets of uncertainty are considered in a PSHA; variability corresponding to the earthquake magnitude, distance, location and time of occurrence, and the uncertainty associated with the source characterization and ground motion attenuation.

The probability of exceeding a certain level of response at a particular ground motion intensity level, $P\left[EDP \mid IM\right]$, is estimated through a probabilistic seismic structural response analysis (PSSRA). A PSSRA extends PSHA to estimate the probability of the structural response conditioned on a certain level of intensity. Different approaches can be used to estimate $P\left[EDP \mid IM\right]$. One approach, Miranda and Aslani [1] is to scale a suite of earthquake ground motions to certain levels of intensity and apply them to the model of the structure through non-linear response history analyses. For each ground motion the response parameters, *EDP*'s, at each story of the building are calculated. Probability parameters of the *EDP*'s, namely measures of the central tendency and dispersion of the response are then computed.

Functions of the probability parameters of the *EDP*'s are developed to integrate $P[EDP|IM]$ over all possible levels of *IM*.

To numerically evaluate Eq. (1) we applied the above procedure to a seven-story reinforced concrete building. A model of the longitudinal direction of the building is developed. A detailed description of the model is presented in Miranda and Aslani [1]. The model is then subjected to a set of 80 ground motion time histories recorded in California. A detailed description of the suite of ground motions can be found in Medina [5]. Figure 1 presents the distribution of the magnitude and distance for the ground motions used in this study. As shown in the figure the ground motions are recorded from earthquakes with magnitudes ranging from 5.8 to 6.9 and with the closest distance to rupture varying from 13 km to 60 km.

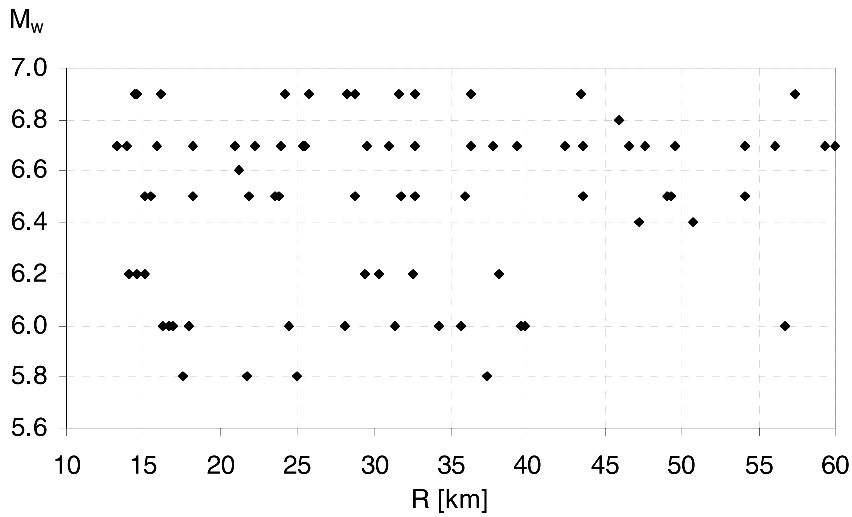

Fig. 1. Distribution of the magnitude and distance of the earthquake ground motions used in this study.

The ground motion intensity measure used in this study is the linear spectral displacement evaluated for a single-degree-of-freedom system with a period of vibration equal to the one of the multi-degree-of-freedom system, S_d. Ground motions shown in Figure 1 are scaled to spectral displacements equal to 2.5 cm, 5 cm, 10 cm, 20 cm, 30 cm, 40 cm, and 50 cm. The building is then subjected to the scaled ground motions. Two types of response parameters at each story of the building are computed: interstory drift ratio, *IDR*, at each story, and peak floor acceleration, *PFA*, at each floor level. The dots in Figure 2 present the results for the *IDR* in the first story and the *PFA* at the roof level.

The probability parameters of the response can then be computed from the dots shown in Figure 2. The lines in this figure present the median response for *IDR* in the first story and *PFA* at the roof level. The probability of exceeding a certain level of *EDP* conditioned on *IM*, $P[EDP|IM]$, can also be estimated from the *EDP*'s calculated at each ground motion. Although, one can numerically estimate this probability distribution, researchers have shown that when the *EDP* of interest is the interstory drift ratio a lognormal distribution can be used for $P[EDP|IM]$. Our studies, Miranda and Aslani [1], show that peak floor accelerations can also be assumed to be lognormally distributed.

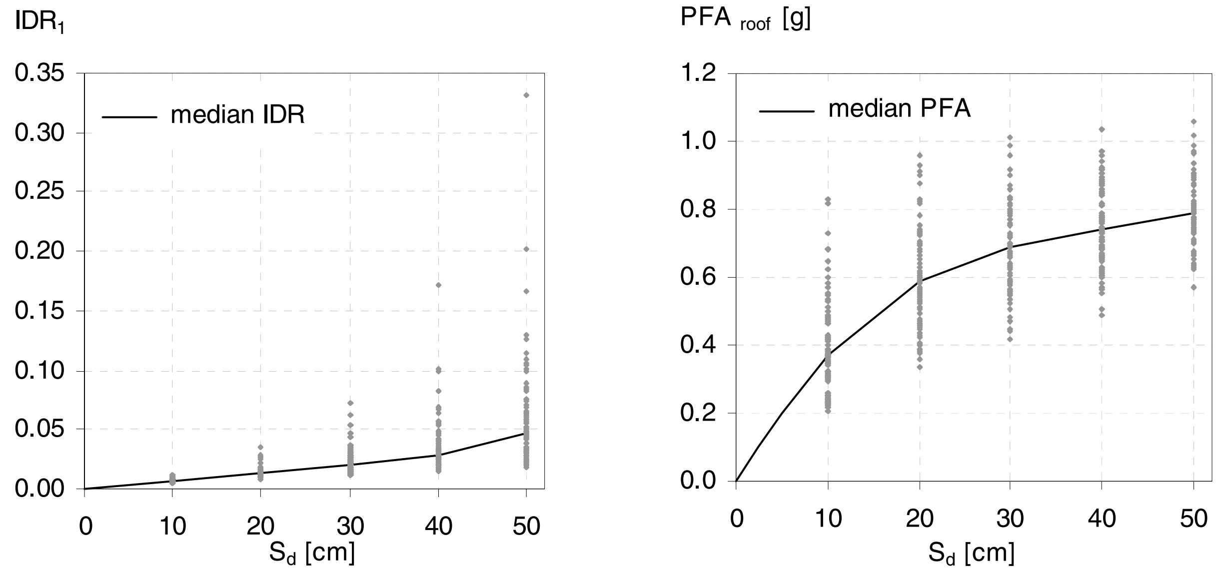

Fig. 2. Interstory drift ratio at the first story and the peak floor acceleration at roof evaluated from 80 ground motions at 5 different levels of intensity.

The seismic hazard at the site, $\nu(IM)$ in Eq. (1) , is estimated based on the readily-available data from the United States Geological Survey, Frankel et al. [6]. Figure 3 presents the seismic hazard curve used in this example.

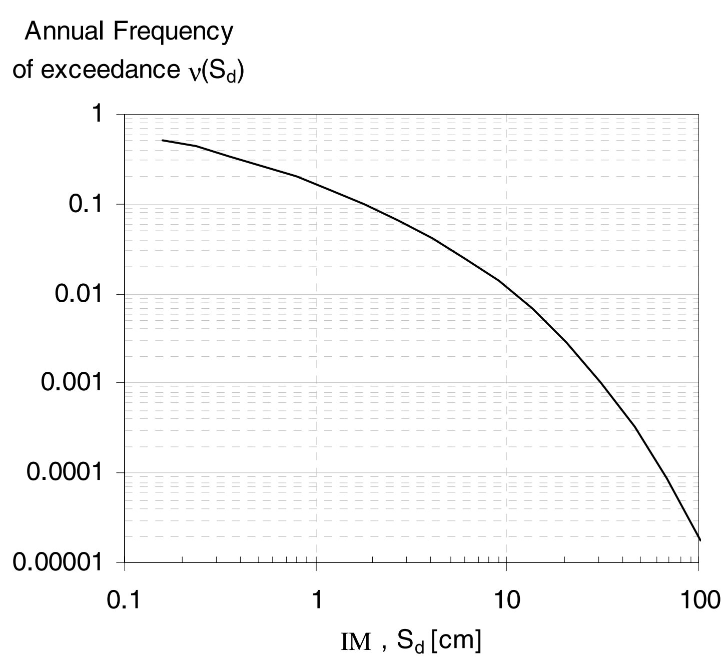

Fig. 3. Seismic hazard curve at the site.

Once the probability of *EDP* at a given scenario, $P[EDP|IM]$, and the seismic hazard at the site have been estimated, we can compute the mean annual rate of exceedance curve for the *EDP* of interest. Figure 4 presents two examples of the numerical integration of Eq. (1) for *IDR* at the first story and roof acceleration, PFA_{roof}. As can be seen the variation of the mean annual rate of exceedance for drift is significantly different from the one of floor acceleration.

The most time-consuming task in PSSRA is running the non-linear response analyses to estimate $P[EDP|IM]$. For example, for the case study building 80 non-linear response history analyses at 7 different levels of intensity were performed. The runtime of the procedure on a Pentium III processor personal computer was approximately 10 hours.

To decrease this run-time a detailed investigation is performed on the required number of runs to capture different probability parameters of the *EDP*. Two types of EDP are investigated; interstory drift ratio, *IDR*, and peak floor acceleration, *PFA*. Both *EDP*'s are required for loss estimation in buildings, since the seismic damage in components are closely correlated to them. Damage in almost all structural components and most of the non-structural components is closely correlated to *IDR*. Damage in some non-structural components is closely correlated to *PFA*. Hence, response optimization is performed for two groups of components; drift-sensitive components and acceleration-sensitive components.

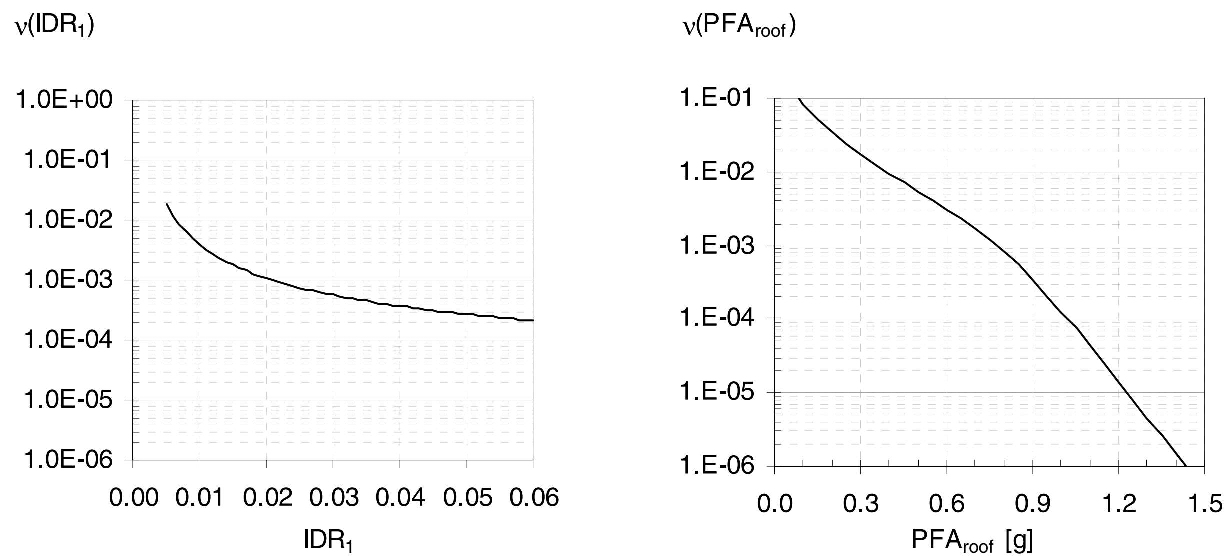

Fig. 4. Mean annual frequency of exceeding *EDP*, for the interstory drift ratio at the first story, IDR_1, and the peak floor acceleration, PFA_{roof}.

PROCEDURE TO OPTIMIZE THE NUMBER OF RESPONSE SIMULATIONS

Four factors can affect the size of the suite of earthquake ground motions to be used in PSSRA: (i) the type of the *EDP* that we would like to estimate; (ii) the probability parameter of the selected *EDP*, for example, median or standard deviation; (iii) the ground motion intensity measure used in the PSSRA; and (iv) the level of intensity at which we would like to estimate the selected parameter of *EDP*.

In this study we considered *IDR* and *PFA* as the *EDP*'s of interest. Three probability parameters for each type of *EDP* are investigated; the median *EDP*, $\tilde{\mu}$, the standard deviation of the natural log of the *EDP*,

σ^* and the mean annual frequency of exceedance of the *EDP*, $\nu(EDP > edp)$. The first two probability parameters are the ones that are required to estimate the probability of exceedance of the *EDP* for a given ground motion intensity, $P[EDP | IM]$. The last probability parameter is investigated to understand if the required number of response histories to estimate the target performance, in this case mean annual rate of exceedance, is less than that required to estimate the intermediate parameters such as the median of the response.

We performed the optimization procedure for two types of intensity measures; elastic spectral displacement, S_d, and inelastic spectral displacement, Δ_i. In this paper, however, the results of the linear elastic intensity measure, S_d, are presented. Furthermore, the optimization is performed at two levels of intensity, S_d = 20 cm , indicative of low levels of intensity, and S_d = 50 cm, indicative of high levels of intensity.

A generic procedure is used to optimize the size of the suite of ground motions to estimate different response parameters. First, we randomly select a certain number of ground motions, *n*. Then, we estimate the response parameter of interest for the selected ground motions. In the next step, the probability parameter of interest, for example median or standard deviation, is computed. The above steps are repeated with replacing the previous selection for a large number of times, for *n* randomly selected ground motions.

The proposed procedure has two important advantages in addition to its simplicity. An important advantage of the proposed procedure is that it is not dependent on the probability distribution of the parameter of interest. Furthermore, the repetition of the procedure allows to find the confidence intervals of estimation of the response parameter for *n* ground motions. Confidence interval represents the level of confidence in the results, which can be modeled as different percentiles for each sample size *n*. For example, a 95% confidence interval is assumed to be the 95th percentile of the random selection of *n* ground motions.

OPTIMIZATION OF RESPONSE SIMULATION FOR DRIFT-SENSITIVE COMPONENTS

Required number of RHA for median drift

Figure 5 depicts the simulation results for the required number of RHA to estimate the median interstory drift ratio at first story, IDR_1, for two levels of intensity, S_d = 20cm and S_d = 50 cm.
The lines presented in the figure are for 95% and 5% confidence intervals. The ordinates for the graphs in Figure 5 represent the ratio between the estimated parameter, shown with "*est*" sub-index, from optimization procedure to the one calculated using all the 80 ground motions in the population, shown with "*exact*" sub-index.

As shown in Figure 5, the required number of RHA, *n*, for median drift is a function of the level of intensity. For example, for a 10% error, $\tilde{\mu}_{est} / \tilde{\mu}_{exact} = 1.1$ or $\tilde{\mu}_{est} / \tilde{\mu}_{exact} = 0.9$, 25 ground motions are required when the intensity level is 20 cm. However, at 50 cm intensity the required number of RHA increases to 35.

Required number of RHA for dispersion of drift

Figure 6 presents the simulation results for the required number of ground motions to estimate the dispersion, standard deviation of the natural log, of IDR_1 for two levels of intensity. As inferred from the figure the number of response histories required to capture the dispersion of the drift is not a function of

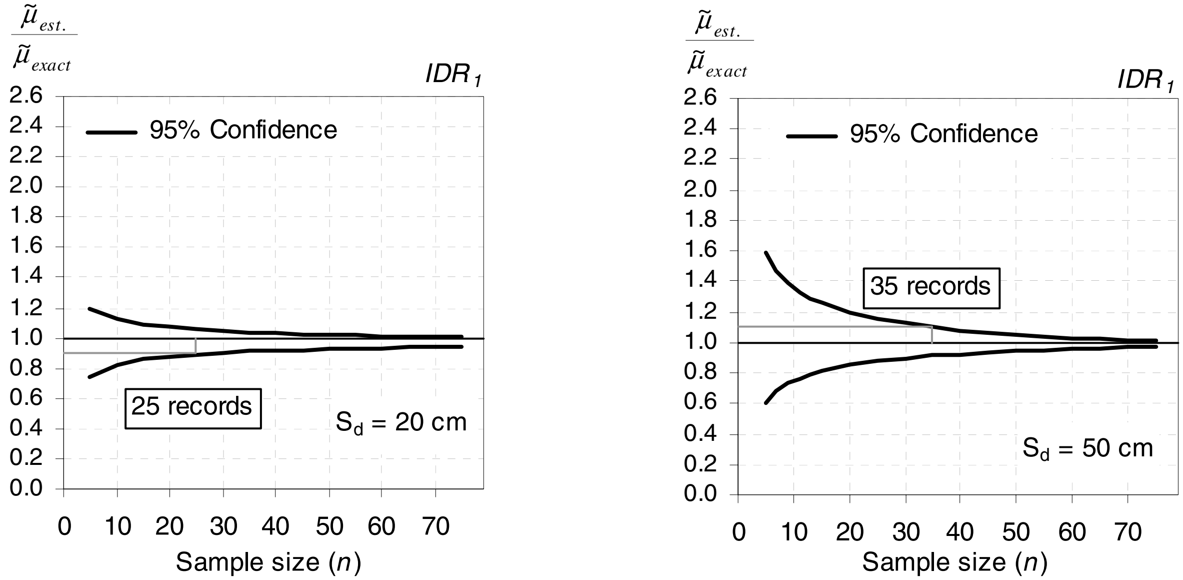

Fig. 5. Changes in the error of estimating the median interstory drift ratio at the first story, *IDR*$_1$, with the sample size for two levels of intensity.

the level of intensity. For example, within a 20% error, $\sigma^*_{est} / \sigma^*_{exact} = 1.2$ or $\sigma^*_{est} / \sigma^*_{exact} = 0.8$, we need around 60 ground motions both at a low level of intensity, S_d = 20 cm, and at a high level of intensity, S_d = 50cm. Another important observation is that the required number of ground motions to estimate the dispersion of the drift within a certain range of error is significantly larger than what is required to estimate the median drift.

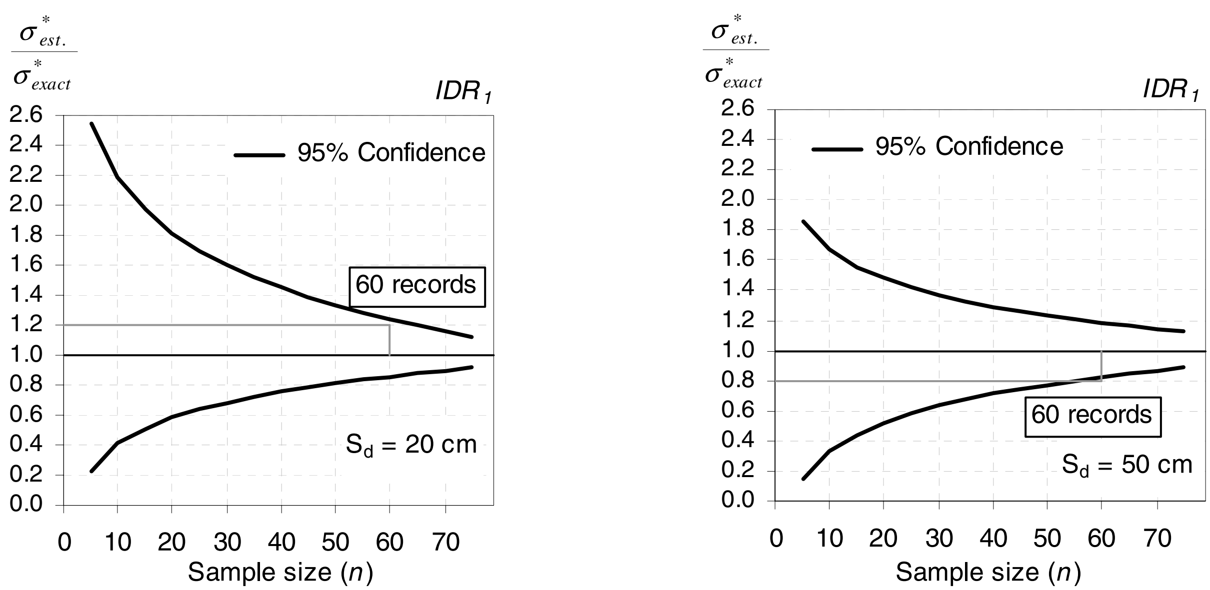

Fig. 6. Changes in the error of estimating the standard deviation of the log of the interstory drift ratio at the first story, *IDR$_1$*, with the sample size for two levels of intensity.

Required number of RHA for mean annual frequency of drift

The procedure to estimate the sample size, *n*, to capture the mean annual frequency of exceeding a certain limit of *EDP* is more elaborate than what is required for the median and the dispersion of the response. In this procedure, for each set of randomly selected ground motions, we perform PSSRA to estimate $P[EDP|IM]$. The estimated conditional probability of *EDP* is then integrated with the hazard curve using Eq. (1).

In Figure 7, we present the procedure at two levels of interstory drift ratio at the first stroy; idr_1 = 0.5 % and idr_1 = 2%. The ordinates in the figure is a measure of error, calculated as the ratio of the ν (*EDP* > *edp*) from the PSSRA for a set of randomly selected ground motion records, shown with "*est*" sub-index, to the one calculated with 80 ground motions, shown with "*exact*" sub-index.

As shown in Figure 7, the number of records required to estimate the mean annual rate changes significantly with the level of deformation. For example, within a 10% error range, it can be seen that 15 records are required to estimate the mean annul drift at 0.5% while 55 records are required to estimate 2% drift mean annual rate.

A very important observation in record optimization for mean annual rate of drift is that the required sample size even at large levels of deformation is smaller than what is required to estimate the standard deviation of the log of the drift. Reducing the sample size results in a significant decrease in the runtime of PSSRA. For example, if 20 ground motions are enough to estimate the mean annual rate with 10% error, the runtime for the case study building decreases by 75%.

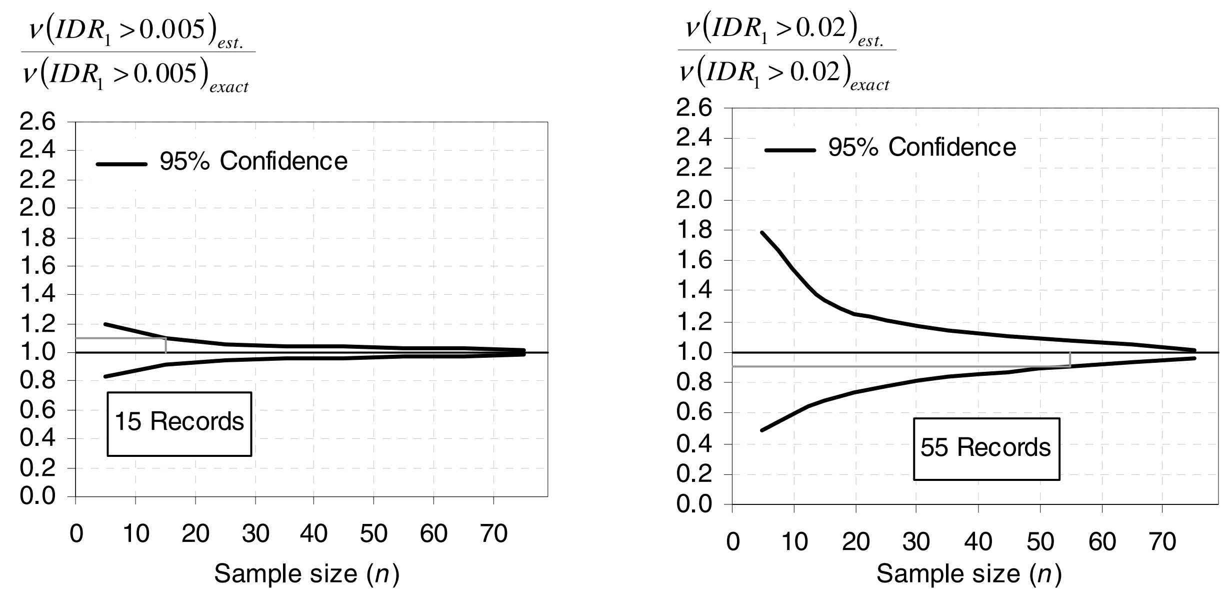

Fig. 7. Changes in the error of estimating the mean annual rate of exceeding the interstory drift ratio at the first story, IDR_1, with the sample size for 0.5% and 2% drifts.

OPTIMIZATION OF RESPONSE SIMULATION FOR ACCELERATION-SENSITIVE COMPONENTS

Required number of RHA for median peak floor acceleration

Figure 8 presents the results for the procedure to obtain the number of response histories required to estimate the median roof acceleration at S_d = 20 cm and S_d = 50 cm. As shown in the figure the required number of records is mainly a function of the level of intensity and decreases with the increase in the level of intensity. For example, for 10% error, 20 response histories are required to capture the median acceleration at S_d = 20 cm , while only 5 records are required when the intensity level is 50 cm.

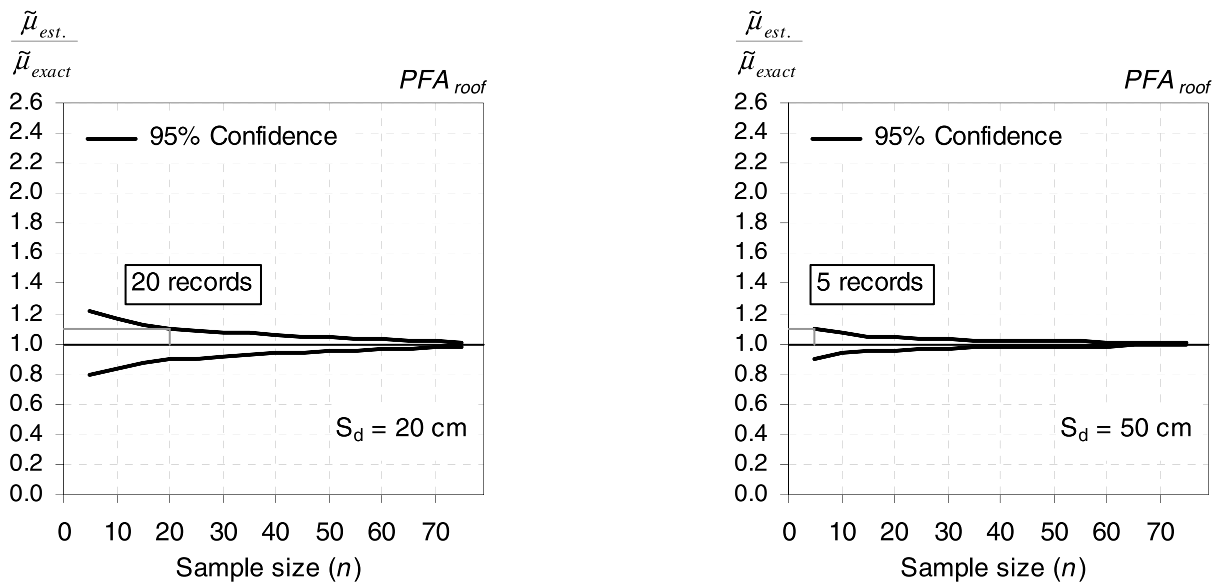

Fig. 8. Changes in the error of estimating the median peak floor acceleration, *PFA* $_{\text{roof}}$, with the sample size for two levels of intensity.

Required number of RHA for dispersion of peak floor acceleration

Figure 9 presents how the error in estimating the standard deviation of the log of the peak roof acceleration decreases with the increase in the sample size. As can be seen in the figure the number of ground motions to capture the dispersion increases with the increase in the level of intensity. For example, 45 analyses are required to estimate the dispersion with a 20% error when the spectral displacement is 20 cm, while 70 response history analyses are required at a spectral displacement of 50 cm.

It is worth mentioning that similar to the observation for drift, the sample size to capture the dispersion is significantly larger than what is required to capture the median acceleration.

Required number of RHA for mean annual frequency of peak floor acceleration

Figure 10 presents the error in estimating the mean annual rate of exceeding peak acceleration at the roof as a function of the number of earthquake ground motions. The information is presented for two levels of deformation; 0.3g and 0.8g.

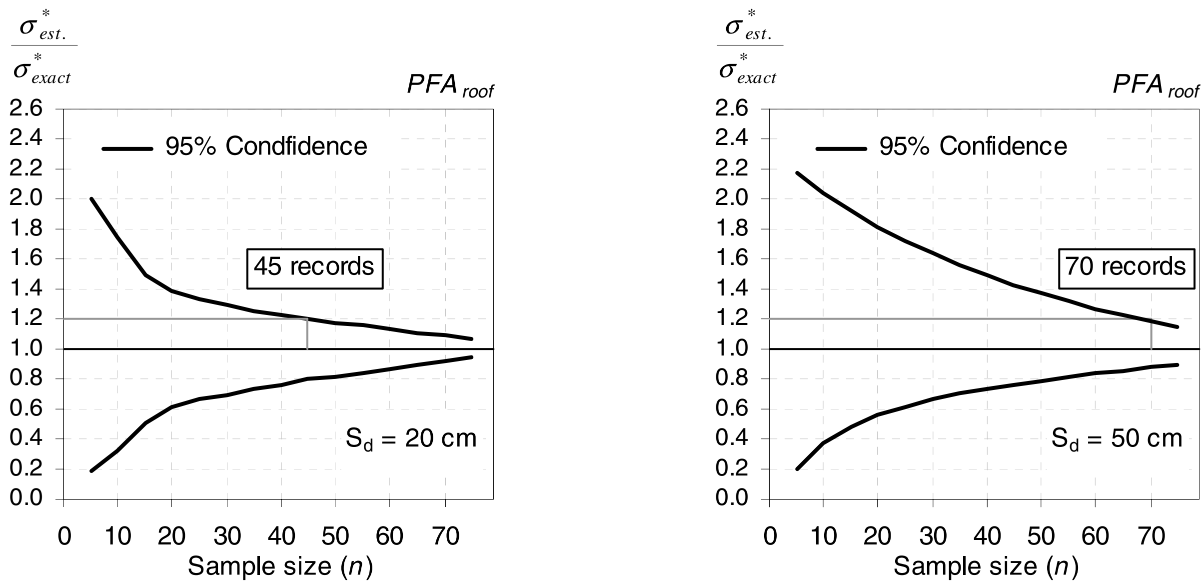

Fig. 9. Changes in the error of estimating the standard deviation of the log of the peak floor acceleration, *PFA* $_{\text{roof}}$, with the sample size for two levels of intensity.

Our investigation on the response optimization for floor acceleration show that the required sample size to capture the mean annual rate of acceleration increases with the increase in the level of deformation. For example, for a 10% error estimation of the mean annual rate exceeding a certain limit, 55 records are needed when the limit is 0.3g, while 75 response history analyses are needed when the limit is 0.8g. The results are counter intuitive since from the observation on the required RHA to capture the median acceleration one would tend to think that the required sample size decreases as the level of deformation increases. The reasoning behind the increase in the sample size with the increase in the level of deformation is currently under investigation.

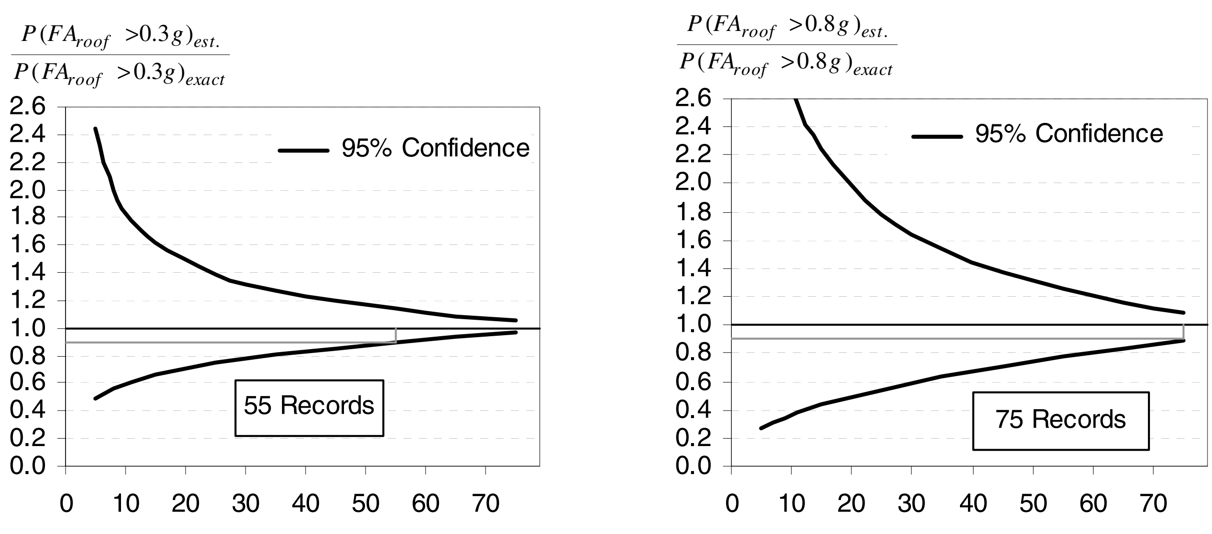

Fig. 10. Changes in the error of estimating the mean annual rate of exceeding the peak roof acceleration, *PFA* $_{roof}$, with the sample size for 0.3g and 0.8g .

CONCLUSIONS

The number of response history analyses to estimate the probability parameters of the structural response with a certain level of confidence has been investigated. The required number of RHA was investigated for three types of probability parameters, namely the median of the response, the standard deviation of the natural log of the response, and the mean annual frequency of exceeding a certain limit of the structural response.

The required number of response history analyses is studied for two response parameters: interstory drift ratio at the first story, IDR_1; and peak roof acceleration, PFA_{roof}, of a seven-story reinforced concrete building. These two responses are required for loss estimation in structural and non-structural components in buildings.

For the case of interstory drift ratio our studies show that the number of records required to estimate the median increases as the level of intensity increases. The number of records to estimate the standard deviation of the natural log, however, does not change with the level of intensity. Our reslts also show that the required number of RHA to capture median drift is larger than what is required to capture the standard deviation of the natural log of the drift.

The number of RHA required to capture the mean annual rate of exceedance for *IDR* is significantly smaller than what is required to capture the dispersion of the drift. This observation has important practical implications, since it allows for a significant decrease in the runtime of the probabilistic analysis without introducing significant error to the procedure. Furthermore, the required number of RHA in this case increases as the level of deformation increases.

For the case of *PFA*, the number of records required to estimate the median response significantly decreases with the increase in the intensity level. The required number of RHA to capture the dispersion of the roof acceleration, however, increases with the increase in the level of intensity. When computing the mean annual rate of exceedance of the roof acceleration, the number of earthquake ground motions increases as the level of deformation increases. Moreover, our investigations show that in general, the estimation of the mean annual rate of exceedance of the *PFA* requires more ground motions than what is required for the same probability parameter of *IDR*.

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