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SEISMIC RISK EVALUATION METHOD OF STRUCTURES BASED ON DEAGGREGATION OF SEISMIC HAZARD

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SUMMARY

In performing seismic PSA (Probabilistic Safety Assessment) of structures, failure probabilities of the structures are usually evaluated from seismic hazard and structural fragility. However, the question arises that the conventional method is based on only one index of seismic ground motions such as peak ground acceleration, and in this case the evaluation of PSA is not necessarily accurate. Although a large number of studies have been made on seismic hazard and seismic PSA, only few attempts have so far been made to answer this problem. The purpose of this paper is to propose a new method which is capable of considering not only single ground motion parameter but also more detailed information on seismic ground motion such as frequency properties and duration time in order to improve the accuracy of reliability evaluation for non-linear structures.

INTRODUCTION

Various uncertainties have to be considered in evaluating structural reliability for earthquakes. Especially, the evaluation of earthquake motions involves large amount of uncertainties and probabilistic seismic hazard analysis (PSHA) has been used to obtain information on earthquake motions and its occurrence. Conventional probabilistic seismic hazard analysis gives seismic hazard curves which show the relationship between the intensity of earthquake motions (i.e., PGA, PGV, spectral response) and its exceedance probability. This seismic hazard curve is useful for engineering purpose because the curve is capable of determining the ground motion intensity corresponding to a target hazard level (i.e., annual probability of exceedance). For example, PSHA has been used to perform seismic PSA for Nuclear Power Plants in U.S. (e.g., Kennedy [1]). However, we cannot obtain more detailed information on earthquake motions such as frequency characteristics and duration time, which are necessary to evaluate seismic reliability of non-linear structures, from the seismic hazard curves.

In order to evaluate dynamic reliabilities of structures more accurately, it is necessary to examine quantitatively how large earthquake parameters such as magnitude and hypocentral distance affect the structural response, especially, non-linear one (Nakajima [2]). In this study, two methods of structural

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failure probability evaluation are examined. The first method proposed is capable of evaluating directly failure probability of structures per year without using seismic hazard curves. In the second method, failure probability is calculated by using earthquake motions which are generated using information given from Probabilistic Scenario Earthquake (Ishikawa [3]; Kameda [4]).

ANALYTICAL MODEL AND CONDITIONS

PSHA method

We use the conventional PSHA method proposed by Cornell (Cornell [5]), in which all earthquakes are assumed to occur according to the stationary Poisson process in the time domain.

Modeling of seismic sources

Generally three types of seismic sources i.e., area-source, intra/interplate large earthquakes and inland active faults are considered in PSHA for Japan. In this study, we use single rectangular area-source model because the purpose of this study is to propose and to develop the methodology and it is easy to incorporate other source models and our proposed method can be applied to realistic seismic hazard models.

Fig.1 shows an imaginary rectangular area source and a site location which are used in the numerical simulation. In this source area, magnitude-frequency relationship is assumed to follow Gutenberg-Richter's formula and the location of earthquakes is assumed to be distributed uniformly and randomly. The maximum magnitude of 8.2 and the minimum magnitude of 5.0 are given and *b*-value in the G-R formula is 0.9 and the number of annual earthquake occurrences for unit area is 2.51×10^{-5}.

Attenuation equation of earthquake motions

Peak ground acceleration (PGA) attenuation equation proposed by Fukushima and Tanaka (Fukushima [6]) is used in this study. Attenuation uncertainty is assumed to follow the logarithmic normal distribution with logarithmic standard deviation ς =0.4835 and the tail of the distribution is cut at the points which are exp($\pm 2.5\varsigma$) away from the median. The equation is formulated as follows;

$$\log_{10} A = 0.51 M_J - \log_{10}\left(\mathrm{R} + 0.006\times10^{0.51 MJ}\right) - 0.0034R + 0.59 \tag{1}$$

in which A is the mean of the peak acceleration (cm/sec^2), R is the shortest distance between site and fault rupture (*km*), and M_J is the JMA (Japan Meteorological Agency) magnitude.

Structure models

In this study, a linear structure model and a non-linear structure model are considered. As a linear structure model, SDOF system whose natural period is 0.2sec and the damping ratio of 0.05 is given. As a non-linear structure model, SDOF system whose natural period in elastic region is 0.2sec and the damping ratio of 0.05 is given. Fig.2 shows the structure model and the relation between structural displacement and restoring force. For the non-linear structure model, we assume that yielding seismic coefficient is 0.41 (=400/980) and failure displacement is 1.5$\times$yielding displacement.

FAILURE PROBABILITY EVALUATION MEHTOD WITHOUT SEISMIC HAZARD CURVE

In this section, we propose a new method which is capable of directly evaluating structural failure probability without using seismic hazard curves and the property of the method is examined by numerical example. Fig.3 schematically shows the flow of the evaluation method.

Procedures of evaluation

The evaluation is performed as follows:

STEP 1: The target area source is divided into two-dimensional meshes as shown in Fig.4. The hypocenters are distributed randomly and the distance R between the site and the hypocenters are calculated. Then the probability density function of earthquake magnitude, $f_M(m)$, which is derived from the Gutenberg-Richter's formula, is evaluated.
STEP 2: Velocity response spectrum $Sv(i, j)$ is determined corresponding to each bin (m_i,r_j). The bins are obtained by dividing the range of magnitude, distance for each seismic source with width Δm and Δr, respectively. Then an earthquake wave which is consistent with the spectrum is generated. Furthermore, another two waves which are consistent with the spectra $Sv(i, j) \pm \exp(\sigma)$ are generated. The σ denotes a logarithm standard deviation of the spectra.
STEP 3: Seismic response analyses of structures are performed by using $i \times j \times 3$ earthquake waves. The mean μ_y and standard deviation σ_y of response y are estimated from the response values, $y_{\mu x}$,. $y_{\mu x \pm \sigma}$,by using earthquake waves compatible with $Sv(i, j)$, $Sv(i, j) \pm \exp(\sigma)$, based on the two-points estimates method (Rosenblueth [7]).
STEP 4: The distribution shape is estimated based on the μ_y and σ_y. Then the probability $P_f(i, j)$ (= Prob[$S>C|\ m_i,r_j$]) that the response value S for earthquake (m_i,r_j) exceeds a limit value of structural resistance C is calculated.
The structural failure probability per year is obtained by the following equation;

$$
\begin{aligned}
P_{f\ /\ year} &= \nu \sum_{i=1}^{n} \sum_{j=1}^{k} f_M(m_i) \cdot f_R(r_j) \cdot \mathrm{Prob}[S > C \mid m_i, r_j] \Delta m \Delta r \\
&= \frac{\nu}{N} \sum_{i=1}^{n} \sum_{j=1}^{k} f_M(m_i) \cdot n(j) \cdot P_f(i, j) \Delta m
\end{aligned}
\tag{2}
$$

where ν denotes the average number of earthquake occurrence per year in the target area source, $n(j)$ is the number of meshes belonging to the j-th bin of the distance, N is the total number of the meshes in the area source and $f_R(r)$ is a probability density function of the distance R.

Relation between proposed method and hazard deaggregation

As is mentioned in the previous chapter, the conventional PSHA method uses single seismic ground motion index such as peak ground acceleration, and detailed information on earthquake motions cannot be obtained from the result. In order to overcome the problem, recently, several methodologies to determine scenario earthquakes based on PSHA have been proposed [e.g., Ishikawa and Kameda [3][4]; McGuire [8]; U.S.NRC [9]]. The concept is called "Deaggregation of seismic hazard", and the earthquake parameters represented by, for example, magnitude $\overline{M}$ and distance $\overline{\Delta}$ for all seismic sources or for each seismic source, are evaluated as one characteristics of the concept. Furthermore, the influence of each seismic source to each hazard level (e.g., annual probability of exceedance) can be assessed quantitatively by defining an index, which is called "contribution factor of seismic sources" (Ishikawa[3]; Kameda[4]).
The bin (m_i,r_j) used in the proposed method is the essential data to perform "Deaggregation of seismic hazard". Moreover, the proposed method can be applied to evaluate the index such as "contribution factor of seismic sources" when real seismic source models are considered. Therefore, we consider that the proposed method in which earthquakes are generated based on the bins, can be included in the concept.

Numerical example

The seismic hazard model and the structure model are used which are described in the previous section. Following the evaluation procedures, the target area source is divided into two-dimensional mesh of $10 \times 10km$ at first. In the area, earthquake occurrence is assumed to follow the Gutenberg-Richter's formula. The distance variable R is defined as the distance between site and the center of each mesh. Tab.1 shows the bins of (m_i,r_j). Then, velocity response spectra by Nishimura et al. (Nishimura [10]) is determined based on (m_i,r_j) and we consider 0.5 as the logarithmic standard deviation of the response spectrum. Fig.5 shows the relationship between the peak values of earthquake motions and the results of time history response analysis. Furthermore, we show the result of fragility evaluation in Fig.6, although the fragility curve is not necessary in the direct method proposed. The failure probability per year calculated from Eq.(2) is 2.971×10^{-2}.

FAILURE PROBABILITY EVALUATION METHOD BASED ON PROBABILISTIC SCENARIO EARTHQUAKE

In this section, we show another method which is based on Probabilistic Scenario Earthquake.

Procedures of evaluation

Fig.7 schematically shows the flow of the evaluation mehtod. The evaluation is performed as follows:
STEP 1: Conventional PSHA, which was developed by Cornell [5], is performed.
STEP 2: Based on the concept of the "Deaggregation of seismic hazard", magnitude M and distance Δ of scenario earthquakes is evaluated corresponding to annual probability of exceedance of earthquake motion's intensity. In this study, we adopt the methodology of Probabilistic Scenario Earthquake (PSE) proposed and developed by Ishikawa and Kameda [Ishikawa [3]; Kameda [4]]. The magnitude $\overline{M}(p_0)$ and the distance $\overline{\Delta}(p_0)$ of PSE, which are defined as the conditional expected value of the magnitude and the distance corresponding to each annual probability of exceedance p_0, are computed by the following equations respectively;

$$\overline{M}(p_0) = \frac{\sum_{k=1}^{n} E_k(M \mid Y \geq y(p_0)) \cdot w_k(p_0)}{\sum_{k=1}^{n} w_k(p_0)} \tag{3}$$

$$\overline{\Delta}(p_0) = \frac{\sum_{k=1}^{n} E_k(\Delta \mid Y \geq y(p_0)) \cdot w_k(p_0)}{\sum_{k=1}^{n} w_k(p_0)} \tag{4}$$

where $w_k(p_0)$ is the annual occurrence rate of earthquakes in seismic source k and which generate seismic intensity at the site exceeding a certain value for a target hazard level p_0.
STEP 3: At each hazard level p_0, earthquake motions which are compatible to response spectrum determined by ($\overline{M}(p_0)$, $\overline{\Delta}(p_0)$) are generated.
STEP 4: Time history response analyses for structure models are performed using earthquake motions which are obtained in STEP 3.
STEP 5: Failure probability of the structure is calculated based on the results of response analysis, and the fragilities are obtained. Then the failure probability per year is evaluated according to the following equation using the information on the exceedance probability of earthquake motions and the fragilities.

$$P_{f\ /\ year} = \int_0^{\infty} p_f(a) \times p_H(a) da = -\int_0^{\infty} \frac{\partial H(a)}{\partial a} p_f(a) da \tag{5}$$

In the equation, $p_f(a)$ denotes the failure probability of the structure for seismic intensity a, $p_H(a)$ denotes the probabilistic density function for a and $H(a)$ denotes the hazard function (curve).

Numerical example

Evaluation of seismic hazard and earthquake motions

Fig.8 shows the seismic hazard curve, the hazard-consistent magnitude $\overline{M}(p_0)$ and the distance $\overline{\Delta}(p_0)$ of PSE respectively. Then, velocity response spectra by Nishimura et al. [10] is determined based on

$(\overline{M}(p_0), \overline{\Delta}(p_0))$ corresponding to each hazard level p_0. Then forty earthquake waves, which are consistent with the spectra, are generated at each p_0. Fig.9 shows the relationship between the PGA in PSHA and the peak value of earthquake motions generated from the PSE. The PGA in hazard analysis is larger than peak acceleration of earthquake waves generated from $(\overline{M}(p_0), \overline{\Delta}(p_0))$. This is because the attenuation equation considers not only the median which is obtained by inputting $(\overline{M}(p_0), \overline{\Delta}(p_0))$ into the equation but also the larger PGA in calculating the probability of exceedance.

Failure probability evaluation

Fig.10 shows the fragility curve for the linear structure model. In Fig.10, the failure probabilities are plotted corresponding to the average of peak acceleration values of forty earthquake waves generated from $(\overline{M}(p_0), \overline{\Delta}(p_0))$. In this case, we assume that failure occurs where the response displacement exceeds the yielding displacement of non-linear structure model. The failure probability per year is computed 2.350×10^{-2} according to Eq.(5).

Fig.11 shows the fragility curve for the non-linear structure model when failure criteria are given by cumulative plastic strain-energy and the failure displacement is considered. In this simulation, we assume that the limit of resistance is evaluated as satisfying the following equation;

$$\frac{E_L}{E_R} = \frac{\delta_U}{\delta_R} \tag{6}$$

where E_L is the limit cumulative plastic-strain energy, E_R is the response cumulative plastic-strain energy, δ_U is the ultimate failure displacement and δ_R is the response displacement in the case of linear structure model. From Eq. (5), the failure probability per year is computed at 4.236×10^{-3} when the peak response is used as the failure criteria, and 1.671×10^{-2} when the cumulative plastic strain-energy is the failure criteria.

DISCUSSION

The result of numerical examples shows that two methods give nearly equal failure probability per year.

The first method can directly evaluate structural failure probability per year where a seismic hazard curve is not required. On the other hand, the second method is characterized by adopting PSE whose parameters are defined as the conditional expected values.

Both methods can be applied to various cases where all kinds of seismic sources such as inland active faults and intra/interplate earthquakes are considered; another type of non-linear structure models are considered with various failure criteria. As the next step of this study, it is necessary to consider the uncertainties contained in the structural system. Moreover, it is also important to examine appropriate bin resolution because the resolution affects on computational time and accuracy in the proposed method.

CONCLUSIONS

In this study, two methods are proposed for evaluating structural failure probabilities per year. Both methods consider information on earthquake parameters such as magnitude and distance corresponding to exceedance probability of seismic intensity and we show by numerical examples that they have possibility of improving the accuracy of failure probability compared with the conventional method in which only the information represented by hazard curve and fragility curve are used.

To develop the proposed method, a further investigation for other seismic hazard models and non-linear structure models is required.

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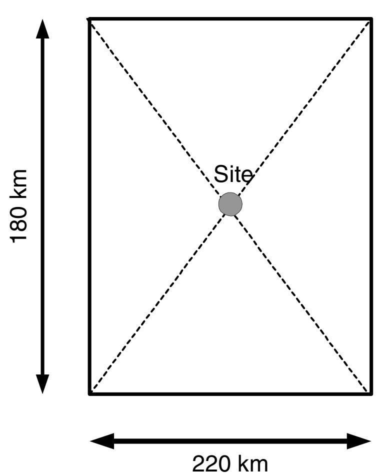


Figure 1: Rectangular area source model

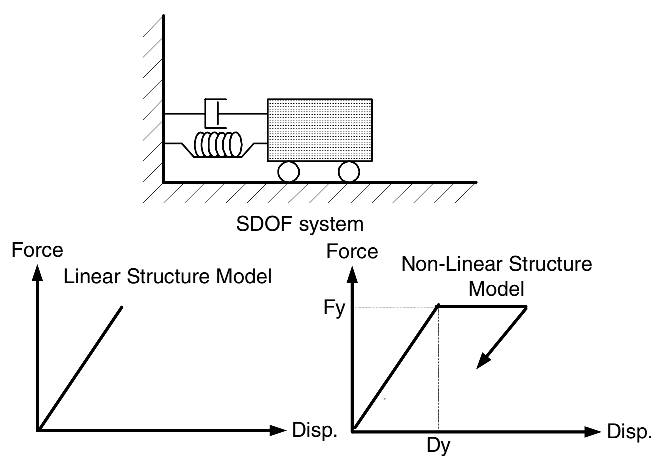


Figure 2: Structure model

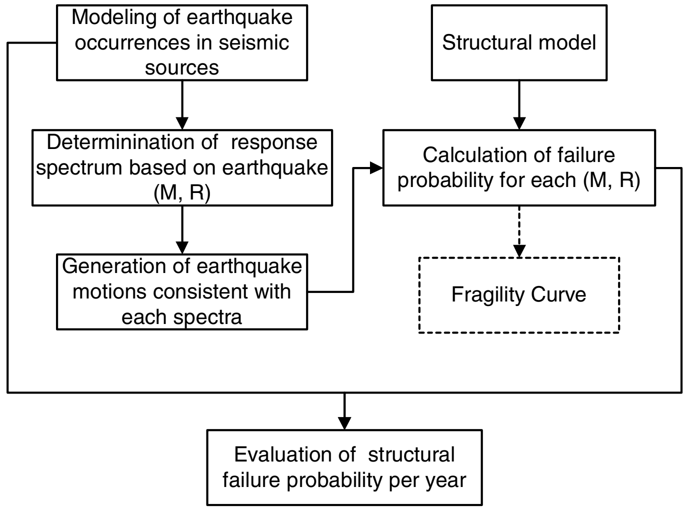


Figure 3: Procedures of failure probability evaluation method-I

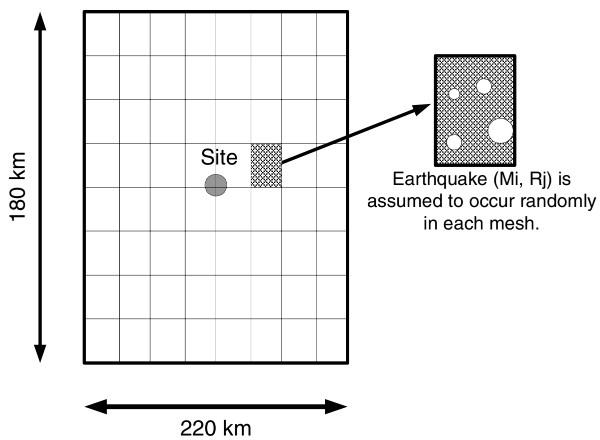


Figure 4: Modeling of earthquake occurrences in target area source

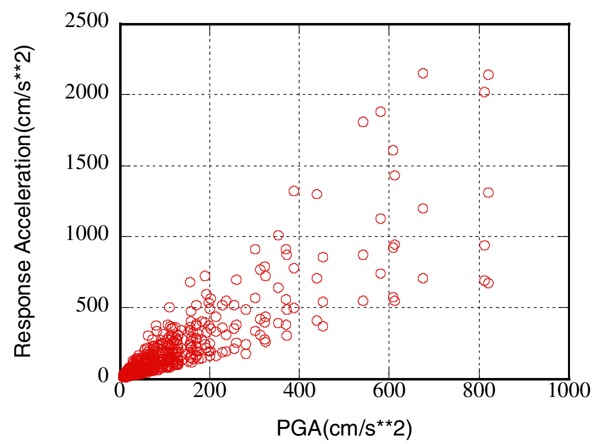


Figure 5: Relationship between the peak values of earthquake motions and the response acceleration

Table 1: Bins of (M,D)

	Magnitude range of bin							
Distance range of bin (km)	5.0-5.2	5.2-5.4	5.4-5.6	....			7.8-8.0	8.0-8.2
0.0-10.0								
10.0-25.0								
25.0-40.0								
40.0-55.0								
55.0-70.0								
70.0-90.0								
90.0-110.0								
110.0-140.0								

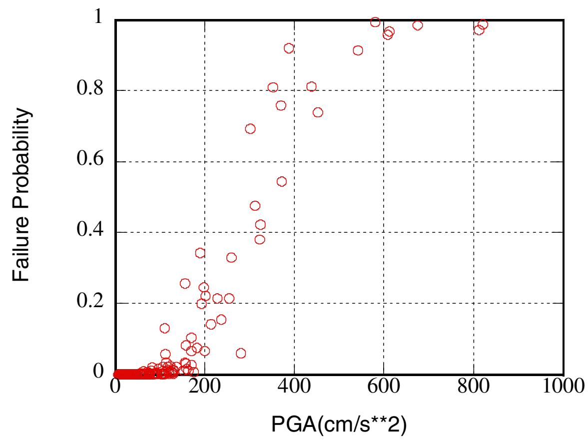


Figure 6: Evaluation of structural fragility

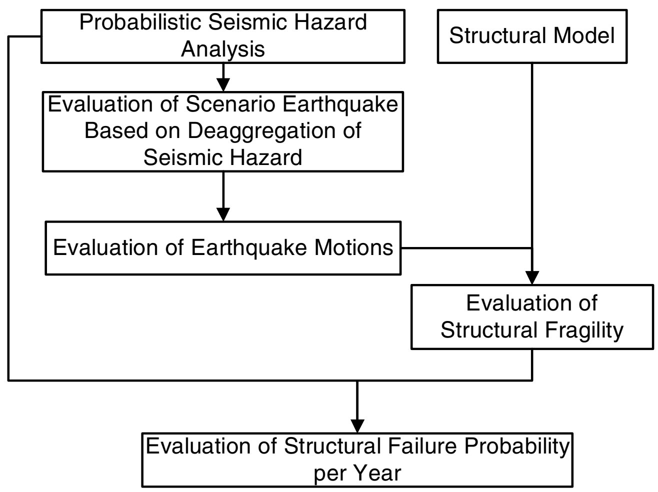
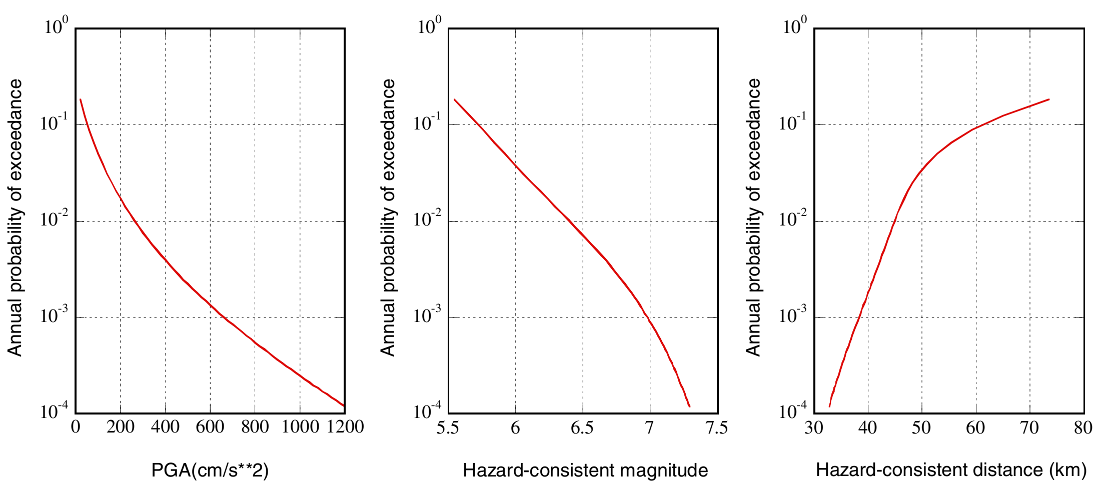


Figure 7: Procedures of failure probability evaluation method-II



(a)Seismic hazard curve **(b)Magnitude of PSE** **(c)Distance of PSE**

Figure 8: PSHA result (PSE: Probabilistic Scenario Earthquake)

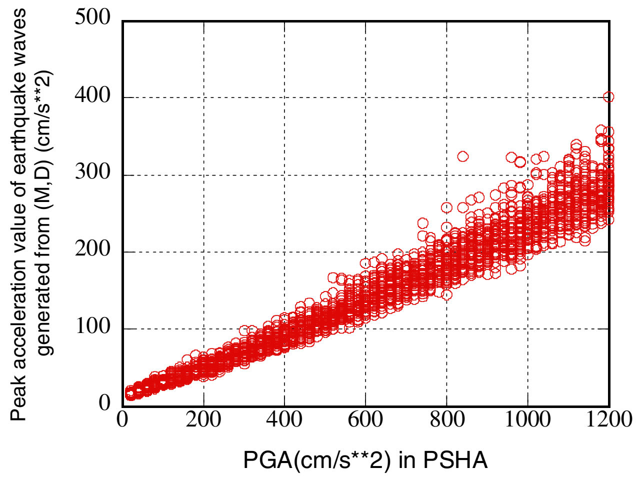
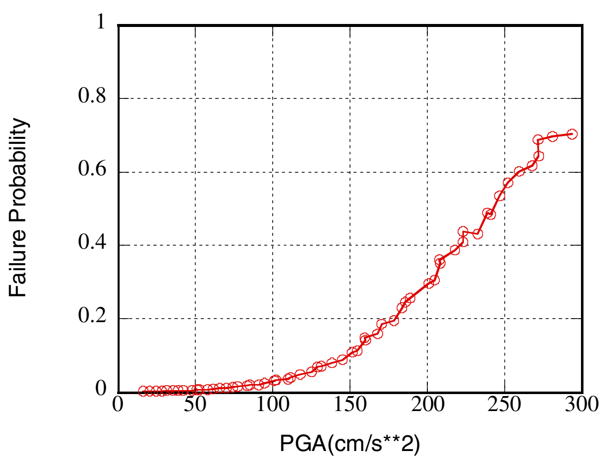


Figure 9: Relationship between PGA in hazard analysis and the peak acceleration of generated earthquake waves



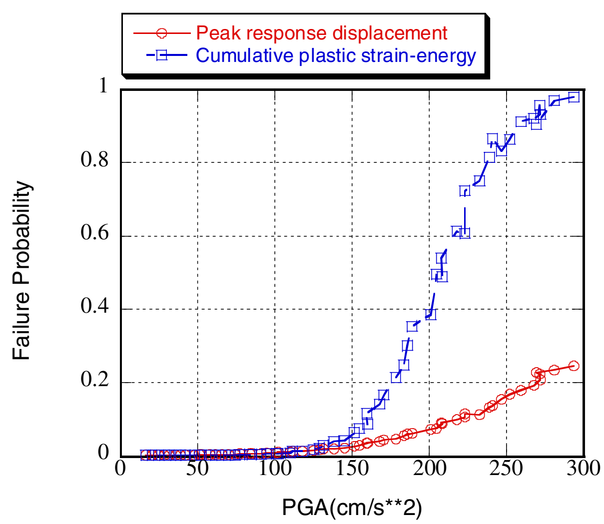


Figure 10: Fragility of linear structure model Figure 11 Fragility of non-linear structure model