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PROBABILISTIC SEISMIC RISK ASSESSMENT OF BASE-ISOLATED RC STRUCTURE

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SUMMARY

Probabilistic seismic risk assessment techniques, which have come to be used for evaluating safety of nuclear plants in recent years, are applied to assess the seismic risk of a base-isolated building. At the first stage, the intensities of earthquakes at the site and the frequency of their occurrences are evaluated. Then, the relationship between peak ground accelerations and failure probabilities is assessed. As a result of seismic risk analysis, it is comprehended that when a base isolation device is used, the probability of failure of building is lowerd, and especially, that of yielding of building is greatly reduced, rather than that of collapse of building.

INTRODUCTION

In recent years, base-isolated buildings have come to be constructed in increasing numbers in Japan and other countries, and considerable amounts of data have also been published. Those results indicate structural responses have been reduced when base-isolated buildings have been subjected to small-scale earthquakes. To evaluate safety of a base-isolated building quantitatively, including safety at times of large earthquakes, the probability theory can be employed. The probabilistic technique(e.g.ref.1) has been developed and often used mainly in the United States for more than a decade to evaluate the safety of nuclear power stations. The buildings studied in this paper are a base-isolated RC building and a RC building with exactly the same super structures constructed on the campus of Tohoku University in Sendai.

I .Seismic Hazard Analysis

The seismic hazard curve expressing the annual exceedance probability for each peak ground acceleration at the site is first evaluated. Next, the probabilistic distribution of the response spectra at the site is evaluated.

1.Evaluation of Seismic Hazard Curve

The hazard curve is evaluated in the sequence of the steps given below in accordance with the method proposed by Cornell(ref.2).

① modeling of the seismic sources with area-sources,
② evaluation of the seismic activity for each seismic source,
③ estimation of the attenuation equation and its uncertainty,
④ calculation of the seismic hazard curve by combining the results.

The area sources are defined as shown in Fig .1 referring the epicenter distribution of historical earthquakes(refs.3,4) and the seismotectonic structures. The attenuation equation proposed by Kawashima et al.(ref.5) on medium soil condition is used, and its uncertainty is taken as 0.516 in terms of logarithmic standard deviation. Fig.2 shows the seismic hazard curve. The figure indicates that the annual probability of exceedance of an earthquake of peak ground acceleration 500gal is 1.2×10^{-3}(1/yr), and that the annual probability of exceedance of that of 1000gal is 4.2×10^{-5}(1/yr).

2. Probabilistic Assessment of Response Spectra (ref.6)

When assessing the expected response spectrum, the following factors are considered: ① the scattering of the response spectra due to the difference of earthquake's magnitudes and epicentral distances, ② the scattering of the averaged response of various levels of the ground motion, ③ uncertainties of the response spectra among the ground motions, whose magnitude and epicentral distance are same. The attenuation equation of response spectra proposed by Kawashima et al.(ref.5) is used for the analysis. The median and the 84-percent non-exceedance curves of the expected spectrum under thecondition of maximum acceleration of 100 to 2000 gal are shown in Fig.3. The result shows that the median response amplification is larger in the short-period range, though the scatter of the spectrum on long-period side is larger.

II. FRAGILITY ANALYSIS

1. Outline of Object Structure and Damage Mode Considered

The buildings studied are a three-story base-isolated RC building and a RC building on ordinary foundation with the same super structures, which as shown in Fig.4, constructed on the campus of Tohoku University. The base-isolated devices are composed of laminated rubber bearings and oil dampers (ref.7). The measured first natural frequency of the base-isolated stucture is approximately 1.4 sec., and the base-isolation devicies are assumed to be elastic in the analysis. Damage modes of the assessment are selected to be a condition of the first-story's yielding and that of reaching the ultimate deformation(collapse), since there is considered a greater possibility of the first story failing rather than the second or third story.

2. Outline of Fragility Analysis

The fragility analysis is performed in accordance with the safety factor method(ref.1) which was firstly applied for Zion plant in the Uuited States. In the safety factor method, a strength A of the building is expressed with the acceleration scale by multiplying a peak ground acceleration A_S by a safety factor F as

$$A = F \times A_S \quad \text{......................... (1).}$$

The safety factor F is expressed by a following equation as a product of a response facter F_R and a capacity factor F_C

$$F = F_R \times F_C \quad \text{........................ (2)}$$

3. Response Factor

The response factor F_R is indicating the safety on a reference response value divided by an expected one as

$$F_R = \frac{\text{Reference Response Value}}{\text{Expected Response Value}} \quad \text{....... (3).}$$

Further, F_R is divided into various response factors shown in Table 1, and it is hypothesized that the respective factors follow logaritmic normal distributions.

The evaluation formulae for the response factors are given in Table 2. The reference response value here is the maximum response shear force of the design model determined by the time-history response analysis with an input motion of El Centro N-S (input maximum acceleration: 100 gal). The Q_{SA50}, Q_{SA84}, Q_{h84}, Q_{MF84} in the table are maximum response shear forces of the building computed under the expected spectrum at the construction site (peak acceleration transformed to 100 gal) by the SRSS Method. The probabilistic distributions of the natural frequencies and the damping constants of each mode are estimated based on the results of vibration tests and micro tremor measurements. Since the expected spectrum in Fig.3 is for a damping constant of 5 percent, transformation should be done for other damping constants according to equations given in ref.5. As for F_{MS}, F_{MC}, F_{SS} and F_{EC} they are estimated based on the engineering judgments.

The computed response factors are given in Table 1. Here, the $\check{F}$ in the table is median of the logarithmic standard deviation of systematic uncertainty(uncertainty relating to the analysis technique and modelling), and βu are logarithmic standard deviation of random uncertainty(uncertainty scattered inherently around median such as scatter of material properties).

4. Capacity Factor

The capacity factor Fc is a safety factor on capacity of the building and it is defined by

$$Fc = \frac{\text{Expected Structural Capacity}}{\text{Reference Response Value}} \quad \text{.....................} (4).$$

Fc is divided into a strength factor Fs and aninelastic energy absorption factor $F\mu$ as

$$Fc = Fs \times F\mu \quad \text{............................} (5)$$

The strength factor Fs is evaluated by

$$Fs = \frac{\text{Expected Strength}}{\text{Reference Response Value}} \quad \text{......................} (6).$$

As factors of uncertainties, equations for the yield and ultimate strength, and the material strengths of reinforcing bars and concrete are considered.

The probabilistic distributions of the reinforcing bars and the concrete are evaluated based on data in ref.8.

The inelastic energy absorption factor $F\mu$ indicates the effect of response values (such as response shear force) being decreased as a result of energy absorption by a structure whose response enters in the inelastic range. In this study, evaluations are made based on the ratios between linear response shear forces and nonlinear response shear forces as shown in Fig.5.

The probabilic distribution of the ductility of the frame are estimated based on the results of experiments on similar ductile RC frames. As for yielding and ultimate shear forces of stories, they are determined based on results of static inelastic analyses. The vibration model used for analyses is a shear-type design model. As input seismic waves, the following five seismic wave records, which were employed at the time of designing, are used : ①Tokachi-oki (Hachinohe Harbor, N-S),②Miyagi-ken-oki (Tohoku University, N-S),③Miyagi-ken-oki (Tohoku University, E-W),④EL Centro (N-S),⑤Taft (E-W).

The capacity factors obtained, as a result of analyses, are shown in Table 3. As this table clearly shows, the capacity factor for the yielding of the base-isolated building is fairly high compared with that of the non-base-isolated building. though the base-isolation building has less inelastic energy absorption capacity

5. Evaluation of Safety Factor

The medians $\check{F}$, the systematic uncertainties βu, and the random uncertainties βr of the safety factors obtained from Fr and Fc for the yielding and the collapse are shown in Table 4. The fragility curve for the yielding in relation to the peak ground acceleration level is given in Fig.6 considering the non-exceedance probability. The figure shows that the median of the peak ground acceleration level at which the base-isolated building yields is approximately 0.95 G, while βu and βr are 0.53 and 0,60, respectively. Similarly, for the non-base-isolated building, the median is approximately 0.18 G, and βu and βr are 0.27 and 0.34, respectively. Of these factors, as shown in Table 1, the uncertainty concerning the spectrum of the base-isolated building is largest. This is because the scatter in the long-period components of expected seismic waves for the site is fairly large.

Ⅲ. ASSESSMENT OF FAILURE PROBABILITY OF BUILDING

Lastly, the hazard curve (Fig. 2) and the fragility curve (Fig. 6) are combined to obtain the annual occurrence probabilities of the failure of the buildings . The results are shown in Fig. 7.

According to this figure, the probabilities of the yielding of the building in case of the base-isolated building will be 1.59×10^{-3}(1/yr) in a median (non-exceedance probability 0.5), and 1.07×10^{-4} to 1.49×10^{-2} (1/yr), if the confidence interval is made 80 percent. Similarly, in case of the ordinary foundation building, they are 9.84×10^{-2} (1/yr) in terms of median (non exceedance probability 0.5), and 3.59×10^{-2} (1/yr) to 2.26×10^{-1} (1/yr), if the confidence interval is made 80 percent. On the other hand, the probabilities of the respective buildings reaching states of ultimate deformation are 6.51×10^{-4}(1/yr) in a median in case of the base-isolated building, and 1.77×10^{-2}(1/yr) in case of the ordinary foundation building.

Ⅳ. CONCLUSION

Probabilistic risk assessment techniques used in recent years were applied to an RC building having base isolation devices and the same RC building with an ordinary foundation, and the probabilities of failures due to earthquakes were investigated. As a result, the building with the base isolation devices had a lower damage probability compared with the building with the ordinary foundation. Especially, the trend was prominent with regard to the yielding of the structure,rather than the collapse. This suggests that the base isolation of the building is particularly effective for an unductile structure such as a RC shear wall structure.

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Table 1 Response Factors

	with Base-isolation System			without Base-isolation System		
	$\check{F}$	β_U	β_R	$\check{F}$	β_U	β_R
Spectral Shape F_{SA}	1.26	–	0.60	0.66	–	0.34
Modal Damping F_h	1.00	0.02	–	1.00	0.04	–
Modal Frequency F_{MF}	1.00	0.46	–	1.00	0.03	–
Modal Shape F_{MS}	1.00	0.10	–	1.00	0.10	–
Modal Combination F_{MC}	1.00	0.20	–	1.00	0.20	–
Soil-Structure Interaction F_{SS}	1.00	0.10	–	1.00	0.10	–
Combination of Earthquake Components F_{EC}	1.00	0.10	–	1.00	0.10	–
Total	1.26	0.53	0.60	0.66	0.27	0.34

Table 2 Evaluation of Response Factors

	Median	Log-Standard Deviation
Spectral Shape F_{SA}	$\check{F} = \frac{Q_D}{Q_{SA50}}$	$\beta = ln\left(\frac{Q_{SA84}}{Q_{SA50}}\right)$
Modal Damping F_h	$\check{F} = 1.0$	$\beta = ln\left(\frac{Q_{h84}}{Q_{SA50}}\right)$
Modal Frequency F_{MF}	$\check{F} = 1.0$	$\beta = ln\left(\frac{Q_{MF84}}{Q_{SA50}}\right)$

Q_D : Referenced Response (El-Centro N-S, A_{max} : 100 Gal)
Q_{SA50} : Shear Response (Spectra : Median, Damping : Median, Frequency : Median)
Q_{SA84} : Shear Response (Spectra : 84% Prob. of Non-exceedance, Damping : Median, Frequency : Median)
Q_{h84} : Shear Response (Spectra : Median, Frequency : Median, Damping : 84% Prob. of Exceedance)
Q_{MF84}: Shear Response (Spectra : Median, Damping : Median, Frequency : 84% Prob. of Exceedance)
$\check{F}$: Median
β_U: Log-Standard Deviation Associated with Uncertainty
β_R: Log-Standard Deviation Associated with Randomness

Table 3 Capacity Factors

Failure Mode	Yielding of the Buildings						Collapse of the Buildings					
	Base-isolation			Non-Base -isolation			Base-isolation			Non-Base -isolation		
	$\check{F}$	β_U	β_R	$\check{F}$	β_U	β_R	$\check{F}$	β_U	β_R	$\check{F}$	β_U	β_R
Strength F_s	7.04	0.0	0.05	1.60	0.0	0.05	7.04	0.0	0.05	1.64	0.0	0.05
Inelastic Energy Absorption $F\mu$	0.97	0.01	-	1.49	0.02	-	1.23	0.03	-	4.98	0.17	-
Total	6.82	0.01	0.05	2.44	0.02	0.05	8.65	0.03	0.05	8.16	0.17	0.05

Table 4 Safety Factors

		Safety Factors			Median Ground Acceleration Capacity (G)
		$\check{F}$	β_U	β_R	
Yielding Stage	with Base-isolation System	8.69	0.53	0.60	0.88
	without Base-isolation System	1.61	0.27	0.34	0.16
Ultimate Stage	with Base-isolation System	10.90	0.53	0.60	1.11
	without Base-isolation System	5.39	0.32	0.34	0.55

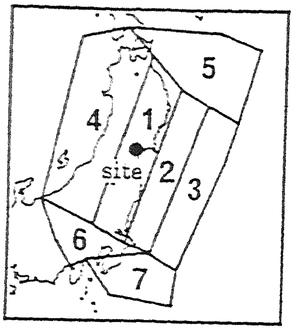
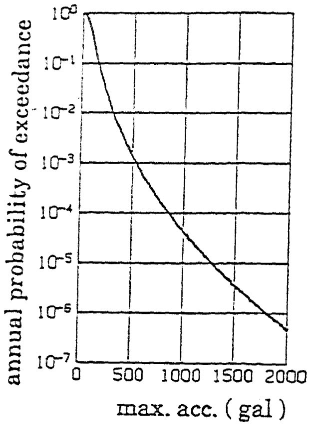


Fig. 1 Seismic Source Areas Model



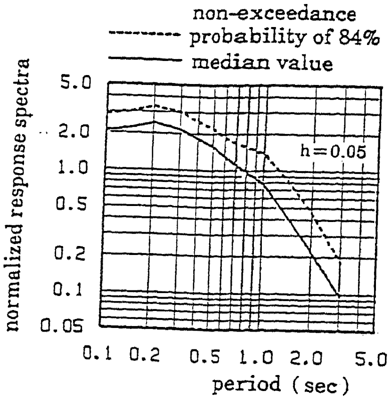


Fig. 3 Normalized Response Spectra

Fig. 2 Seismic Hazard Curve

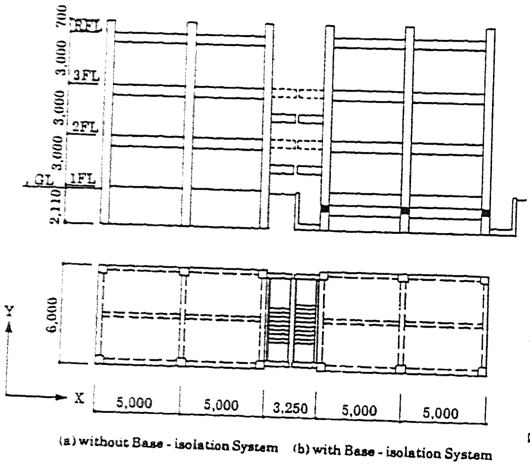


Fig. 4 Three - story RC Buildings

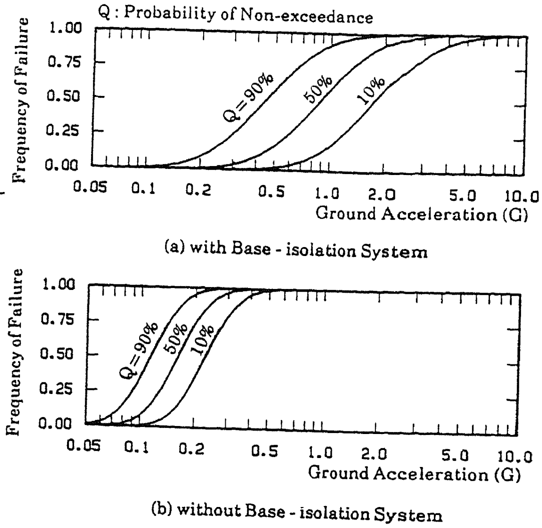


Fig. 6 Fragility Curves

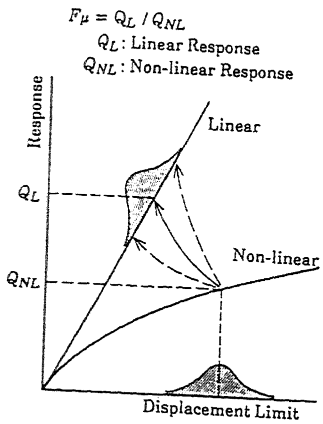


Fig. 5 Evaluation of F_μ

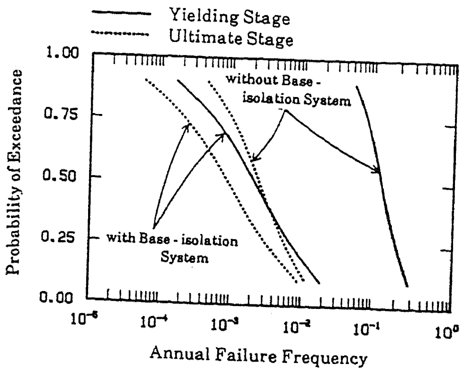


Fig. 7 Probability Distribution for the Annual Frequency of Failure