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Response analyses considering uncertainties of structural characteristics for base-isolated reactor building

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ABSTRACT : Seismic response analyses for the base-isolated reactor building were conducted with considering uncertainties of structural characteristics. This paper describes the results of two examinations, which were quantitatively to evaluate the influence degree of such uncertainties on the response in the case of the design of the above building and to estimate the seismic safety margin against the design earthquake through the reliable probability approach. Further, these analyses were conducted based on the Monte Carlo simulation technique.

1. INTRODUCTION

It is necessary to grasp the variability of the building response resulting from the possible uncertainties in the material properties of the structure, soil and so on in the case of the design of the base-isolated reactor building. The objectives of this paper are the followings;

- It is to investigate what factor in structural characteristics should be especially considered in the design of the base-isolated reactor building and the equipment included in such a building
- It is to investigate that the base-isolated building secures the enough seismic safety margin as well as the seismic designed building from the viewpoints of failure probability assessment.

Two studies as shown under were conducted;

1) Horizontal seismic response analyses and vertical ones to evaluate the influence of such uncertainties on the building response and the floor response spectra for the design earthquake.
2) Fragility analyses to estimate the seismic safety margin from the viewpoint of probability.

These analyses were conducted based on the Monte Carlo simulation technique with the variability of those selected factors considered(Sample:100).

2. INFLUENCE DEGREE ON RESPONSE

2.1 Estimation of uncertainty for the design factor

The uncertainty of the possible design factor that have an influence on the response of base-isolated building was investigated and its value is estimated on the basis of past experimental results or analytical studies.

The analytical models were made based on base-isolated Fast Breeder Reactor (FBR) building designed in Japan[1]. The models are single-stick lumped mass model considering both isolation layer and soil-structure interaction as spring. The design specifications of base-isolation system are shown in Table 1 and Fig. 1. respectively. The combination of natural rubber bearing and steel damper were used for base-isolation system as representative. The uncertainty of input-motion is not considered in this section.

The factor was arranged in terms of the parts of analytical model; soil spring, rubber bearing, steel damper and building.

The uncertainty of soil spring was represented in that of the shear wave velocity Vs. The value of uncertainty for Vs was estimated as 0.10 in the coefficient of variation (abbreviated as COV). Stiffness and damping coefficient of soil spring (horizontal, rotational and vertical) were set as proportional to the square of Vs and Vs itself, respectively.

In the case of the rubber bearing (abbreviated as Isolator), horizontal and vertical stiffness were considered. The uncertainty was evaluated based on accepting tests of actual building. The COV of horizontal and vertical stiffness were estimated as 0.05 and 0.10, severally, and were set as independent each other. The rotational stiffness was set as proportional to the vertical one.

The uncertainty of characteristics of steel damper was represented by that of material. The COV of the stiffness and yield strength were estimated as 0.03 and 0.10, respectively.

The design strength of concrete Fc was considered to be the representative for the design factor of building. The COV of Fc is evaluated as 0.13. Shear stiffness and axial stiffness of building were set as proportional to square root of Fc.

2.2 Uncertainty of response and effective design factor

The preliminary studies evaluating the sensitivity of each design factor were done by considering the variety of each factor one by one. Design factors that have great influence on horizontal and vertical response results are selected as shown in left part of Table 2 and Table 3, respectively. In the case of horizontal response, all characteristics of soil spring and the rotational spring of isolation system were neglected since their influence were very little.

By considering the uncertainties of selected design factors, horizontal and vertical response analyses were performed as follows.

(1) Make 100 samples of each factor according to the normal distribution by using the design value (as mean value) and COV.

(2) Carry out the response analysis using these samples of all factors in random order. Evaluate the uncertainties of response value from this case, named “All Variable”.

(3) Carry out the response analysis considering one factor as fix, while the other factors are varied. Evaluate the influence of each design factor comparing these results each other or with that of (2).

Table 2 and Table 3 show analysis cases. The extreme design earthquake S_2-D[1] with maximum accelerations of 380 cm/sec^2 is used as input wave.

Following three response values were evaluated and analyzed statistically; horizontal displacement of bearing, horizontal and vertical floor response spectra (FRS) at the support point of the reactor vessel (h=0.01).

Fig. 2 shows the example of FRS in the case of vertical “All Variable”. The FRS was represented by Rmax; maximum value in effective range for equipment as shown in Fig. 3.

Fig. 4 shows the distributions of horizontal displacement of isolator. It varies around 0.07 for COV. It is confirmed that the strength of steel damper has a great influence, though the other design factors such as the stiffness of rubber bearing have small influence..

Fig. 5 shows the distributions of vertical FRS represented by the Rmax. It varies around 0.1 for COV. The shear wave velocity of soil Vs shows dominant effect, while other design factors affect little.

In the case of horizontal FRS, the design strength of concrete Fc has the greatest influence and the stiffness of steel damper has smaller. The effect of other factors is negligible..

3. FRAGILITY ASSESSMENT

3.1 Procedure

The seismic safety margin of the base-isolated building against the design earthquake was estimated through the reliable probability approach.

The object of the building and the variability of structural characteristics were the same as the above, but the non-linear characteristics of the superstructure, isolators and the soil were additionally considered in the analytical model.

Fig. 6 shows the variability of the skeleton curve (structural characteristics). The mean of the skeleton curve was the design value, but the mean for the shear walls was evaluated assuming that the concrete strength Fc was 1.5 times the design value based on the actual building. The variability were considered in G, τ_1, τ_2, τ_3, γ_1, γ_2 and γ_3 for shear walls, K_{GH} and γ_{Gu} for isolators, K_D and Q_D for dampers, where ,as for G, τ_1 and τ_3, the randomness due to themselves based on test results were considered in addition to that due to the design estimation by the variable Fc. The mark of shade and white in Fig. 6 signify the independence and the dependence on another factor, respectively.

The design input earthquake was changed to the imaginary earthquake S_2[2] with the velocity of 200kine in the relatively long period contents and the maximum acceleration of 830cm/sec^2 (PGA), which is considered to be the greatest earthquake in Japan.

As for the design specification of isolation system, the yield coefficient β of 0.05 was changed to 0.10. But the isolated natural period T_1 and T_2 were the same as the above study. The combination of natural rubber bearing and steel damper was considered for the isolation device.

The response variability βs, which was employed in fragility assessment, was evaluated through the non-linear seismic response analyses with the amplified earthquake S_2. The variability βu due to the uncertainty (see Table 4) was evaluated as the analytical error by comparison between the response analyses and the shaking table test results[3].

3.2 Results

Fig. 7 shows the response results of the typical members (shear wall of 1st-story and isolation layer). Fig. 8 shows the mean and standard deviation of such results by relationship with PGA.

The response of shear wall increased like the square curve of PGA, but the one of the isolation layer increased almost linearly(see Fig. 8). The COV of shear walls fluctuated due to the degree of the non-linearity, but the COV of the isolation layer was almost constant. In this paper, the response variability βs was estimated from the results at 2.5S_2 input level with engineering judgment, since the collapse of shear walls and rupture of isolators occurred at 2.5S_2 input level.

As for the responses at the support point of the Reactor Vessel, the maximum response acceleration(ZPA) increased like the square curve of PGA, as shown in Fig. 9(a). But the variability increased gradually in proportion to PGA (see Fig. 9(b)).

The probability of failure was calculated by the expression as shown in footnotes of Table 4, where the relationships between the mean of response(S) in each member and the input level(PGA) was evaluated due to the regression analysis. Table 4 shows the results of the fragility assessment of base-isolated reactor building.

Fig. 10 shows the fragility curves with estimated by 95% confidence for all members. Probability of failure for this building was estimated to be Pf=1.38×10^{-9}, where that of the isolation layer was the greatest. From the viewpoint of the reliability based design, the allowable probability of failure in the Western countries is shown to be Pfa =10^{-5}-10^{-7} as a tentative proposal for the concrete containment vessel, which is the most important structure in nuclear power plant facilities[4]. As the above Pf was much less than this proposal notwithstanding that the results of hazard analysis were not considered, it was confirmed that this building has the enough seismic safety margin.

In this connection, the value of the High Confidence Low Probability of Failure(HCLPF), which is alternative safety standard, was 1390cm/sec^2 (1.67S_2).

4. CONCLUSION

It was verified that the uncertainty of the yielding strength of damper has a tremendous influence on the response displacement of the isolator, which is considered to be an index as the seismic safety margin, though the uncertainty of the stiffness of the isolator has a little influence.

As for the horizontal response spectra at the support point of the R/V, the COV was calculated to be 5% to 10%, which was considered not effective to the design of equipment. On the other, the COV of vertical response spectra at the same point was calculated to be 10%, wherefore the uncertainty of the stiffness of the soil has the greatest influence on it.

From the result of the fragility analyses, which were conditioned that the input earthquake S_2 used was only the greatest tentative earthquake in Japan, the probability of failure assessment at wave S_2 level for the components (shear walls or isolators) of the base-isolated reactor building were lower than the order of E-8. Therefore it was verified that the base-isolated reactor building secured enough the seismic safety margin for the earthquake.

5. ACKNOWLEDGMENT

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Table 1 Design specification of isolation system

Direction	Property	Value
Horizontal	Initial period T1	1.0 sec
	Isolated period T2	2.0 sec
	Yield coefficient β	0.05
Vertical	Natural period Tv	0.05 sec

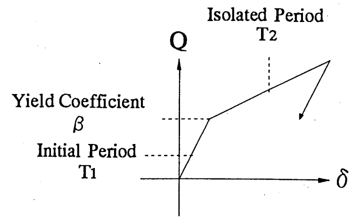


Fig.1 Characteristics of isolation system

Table 2 Considered uncertainties and analysis cases for horizontal response

Uncertainties			Analysis case				
Member	Factor	COV	All Variable	Fc Fix	Khi Fix	Kks Fix	Qhs Fix
Building	Concrete Strength Fc	0.13	Var.*	Fix*	Var.	Var.	Var.
Isolator	Stiffness Khi	0.05	Var.	Var.	Fix	Var.	Var.
Damper	Stiffness Khs	0.03	Var.	Var.	Var.	Var.	Var.
	Strength Qhs	0.10	Var.	Var.	Var.	Var.	Fix
Number of case			100	100	100	100	100

*Var. : Consider its variety Fix : Fix it as mean value

Table 3 Considered uncertainties and analysis cases for vertical response

Uncertainties			Analysis case			
Member	Factor	COV	All Variable	Fc Fix	Kvi Fix	Vs Fix
Building	Concrete Strength Fc	0.13	Var.	Fix	Var.	Var.
Isolator	Stiffness Kvi	0.10	Var.	Var.	Fix	Var.
Soil	Shear Velocity Vs	0.10	Var.	Var.	Var.	Var.
Number of case			100	100	100	100

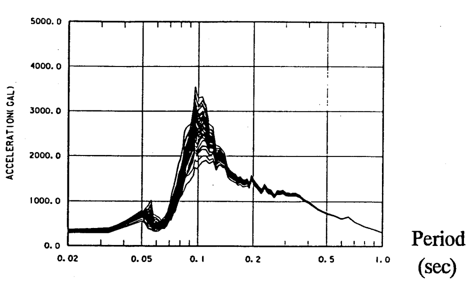


Fig.2 Example of vertical FRS "All Variable"

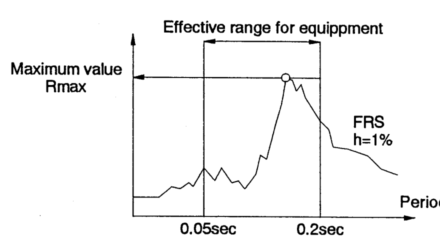


Fig.3 Evaluation of FRS by Rmax

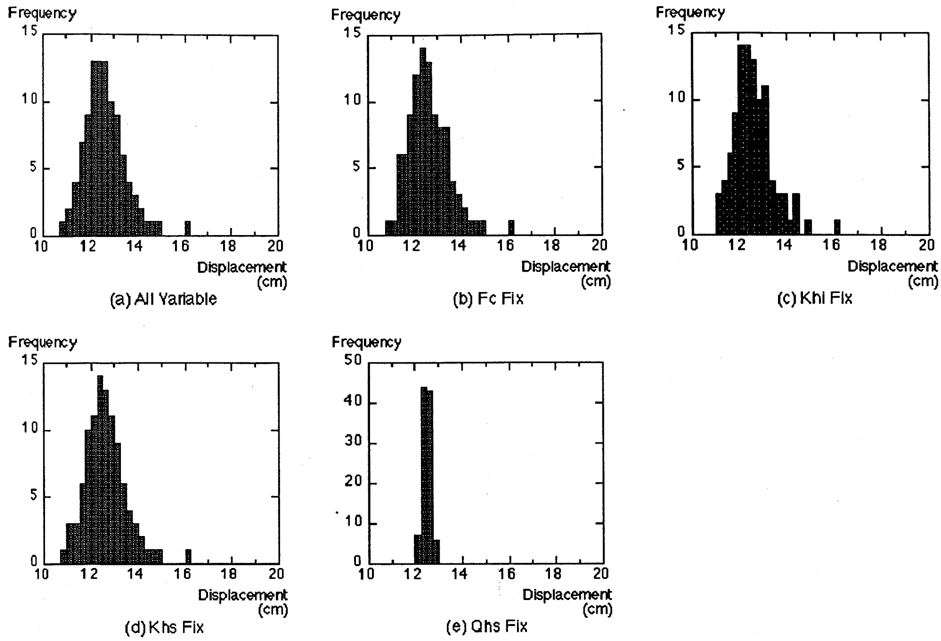


Fig. 4 Distribution of Horizontal Displacement of Isolator

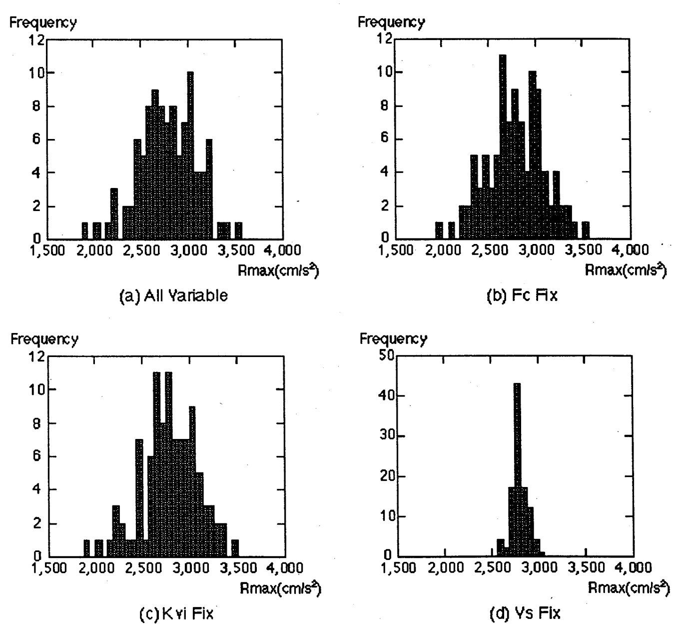
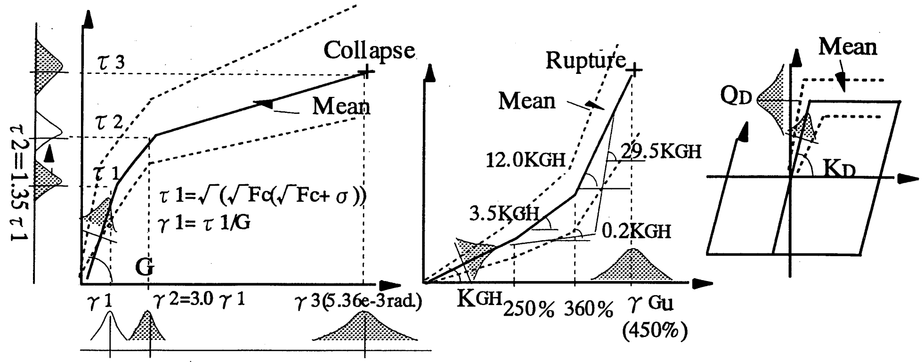
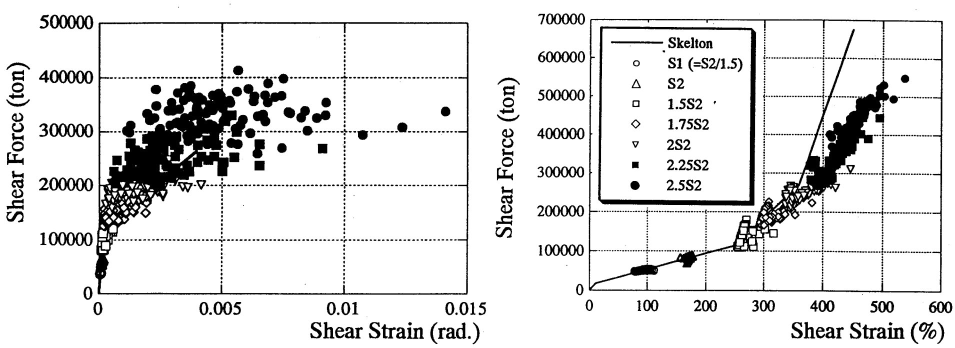


Fig.5 Distribution of Vertical FRS Represented by Rmax



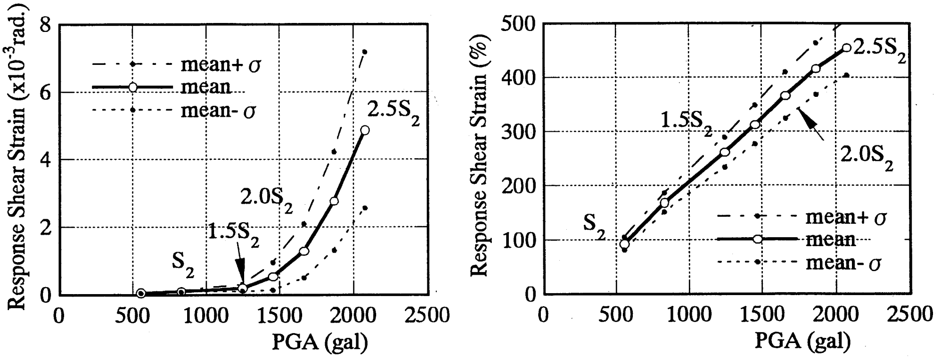
(a) Shear wall (b) Isolator (c) Damper

Fig. 6 Variability of skelton curve (structural characteristics).



(a) Shear wall of 1st-story (b) Isolators

Fig. 7 Results of response analyses at input level S2/1.5 - 2.5S2.



(a) Shear wall of 1st-story (b) Isolators

Fig. 8 Mean and standard deviation of response.

Table 4 Results of Fragility assessemt

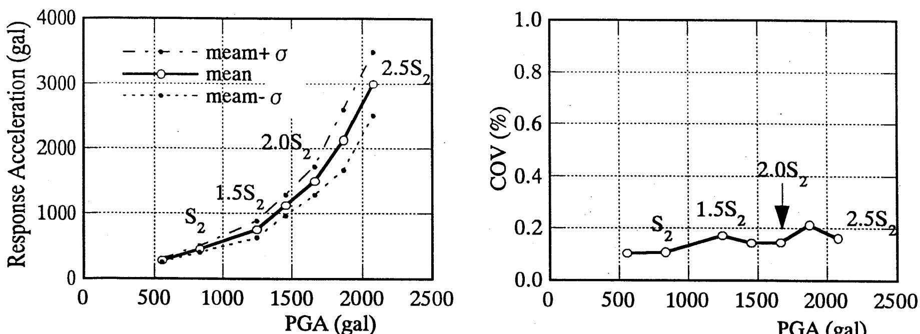
Member	Randomness					Uncertainty	Fragility assessment	
	Response (2.5S2)		Capacity		βR			
	COV	βs	COV	βr	$\sqrt{\beta s^2 + \beta r^2}$	βU	Pf*1	HCLPF
8th-story	0.509	0.480	0.31	0.303	0.568	0.15	1.1×10^{-15}	1900gal
7th-story	0.358	0.347	0.31	0.303	0.461	0.15	2.0×10^{-16}	1670gal
6th-story	0.426	0.408	0.31	0.303	0.508	0.15	1.5×10^{-13}	1740gal
5th-story	0.570	0.530	0.31	0.303	0.610	0.15	2.3×10^{-11}	1890gal
4th-story	0.466	0.443	0.31	0.303	0.537	0.15	3.1×10^{-13}	1830gal
3rd-story	0.449	0.429	0.31	0.303	0.525	0.15	9.9×10^{-13}	1730gal
2nd-story	0.452	0.431	0.31	0.303	0.527	0.15	1.7×10^{-13}	1760gal
1st-story	0.472	0.448	0.31	0.303	0.541	0.15	2.5×10^{-11}	1720gal
Iso.-layer	0.113	0.113	0.078	0.078	0.137	0.10	1.4×10^{-9}	1390gal

β : logarithmic standard deviation$=$ $(\ln(1+\mathrm{COV}^2))^{1/2}$

*1 :

$$Pf = \Phi\left[\frac{\ln(S/R) + \beta U \Phi^{-1}(Q)}{\beta R}\right],$$

in which Pf is the probability of failure, S and R are respectively the mean of response and capacity of a member, and $\Phi(\,)$ is the standard Gussian cumulative function.



(a) Mean and standard deviation (b) Variability of response acceleration

Fig. 9 Responses at supporting point of Reactor Veseel.

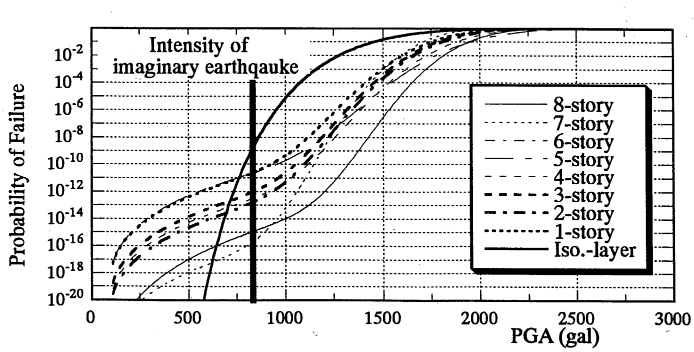


Fig. 10 Fragility assessment for base-isolated reactor building(95% confidence curves).