Comparison of Evaluation Methods for Response Factor in Structural Fragility Analysis

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1. INTRODUCTION

In probabilistic seismic risk assessment for Zion nuclear power plant in USA, structural fragility analysis based on SRSS method (Square Root of Sum of Square method) was adopted for calculation of response factors of which safety factor consists. The advantage of adopting SRSS method is that it is possible, however approximately, to get maximum response value simply by using data of vibrational characteristics for system when spectrum characteristics for an earthquake are decided.

In this paper, response factors relating to material properties of soil and structure, which make up safety factor, are calculated by simple method based on SRSS method and by detailed method based on MCS method (Monte Carlo Simulation method) respectively, and then the influence on probability of fragility for reactor building caused by the difference between both methods are investigated.

As the result of comparison for response factors calculated by simple method and detailed method, it is cleared that, judging from engineering point of view, the difference of response factors between both methods are small enough, that is, the difference influences only a little on probability of fragility, so it is confirmed that SRSS method is available as simple method.

2. METHOD OF DEFINITION FOR RESPONSE FACTORS

In safety factor method, each response factors mean safety margins on respective uncertainty contained by design response values. But it is not always suitable to consider all uncertainty in seismic design flow as response factors for analytical model. This is because that each subdivided response factors cause unclearness of respective meanings itself and cause difficulty to estimate each subdivided response factors distinctively. So in the case of considering response factors, it is much important to take account of applicability for the assumption that respective factors have no correlations each other, and to take account of applicable limitation for data and methods of estimate. And so, in this paper, in the view point of above mentioned, four response factors, described as follows, are considered as main certainty in the standard seismic design for nuclear power plant in Japan. Therefore, response factor of structure is defined as multiplication of four response factors as shown Eq. (1).

$$\text{Response Factor: } F_R = \frac{\text{Design Response Value}}{\text{Real Response Value}} = F_{SA} \cdot F_{SO} \cdot F_{ST} \cdot F_{MO} \quad \cdots\cdots (1)$$

Each response factors mean safety margins contained by design response value through respective design steps described as follows.

(1) F_{SA} : Safety Margin for Design Spectrum Shape

F_{SA} means safety margin contained by design spectrum shape of input earthquake decided by seismisity around model site. On the other hand, probabilistic distribution of spectrum shape computed by seismic hazard analysis based on historical seismic data is regarded as real spectrum shape at model site. Fig. 1 shows design spectrum shape at the site for structure, and shows median and 84% non-exceedance value of real spectrum shapes taken in this paper.

$$F_{SA} = \frac{\text{Response Value by Design Spectrum Shape}}{\text{Response Value by Real Spectrum Shape}} \quad \cdots\cdots\cdots\cdots (2)$$

(2) F_{SO}: Safety Margin for Characteristics of Soil

F_{SO} means safety margin contained by soil material properties for design

$$F_{SO} = \frac{\text{Response Value by soil material properties for design}}{\text{Response Value by real soil material properties}} \quad \cdots\cdots\cdots (3)$$

(3) F_{ST}: Safety Margin for Characteristics of Structure

F_{ST} means safety margin contained by material properties of structure for design.

$$F_{ST} = \frac{\text{Response Value by material properties of structure for design}}{\text{Response Value by real material properties of structure}} \quad \cdots\cdots (4)$$

(4) F_{MO}: Safety Margin for Design Response Analysis Model

F_{MO} means safety margin contained by idealized structure model for design response analysis. In this paper, design response analysis model is multi-lumped masses system with sway and rocking springs, and response value of the model is calculated by using observed seismic wave at the site. On the other hand, actual response value of the structure observed during the earthquake is regarded as real response value.

$$F_{MO} = \frac{\text{Response Value by Design Response Analysis Model}}{\text{Actual Response Value of Structure}} \quad \cdots\cdots\cdots (5)$$

Among those response factors as above mentioned, F_{MO} is decided by quoting from the reference as shown Table 1, and F_{SA} is obtained from another investigation as also shown Table 1.

F_{SO} and F_{ST} are calculated by detailed method based on MCS method and simple method based on SRSS method as following described.

3. METHOD OF ESTIMATE FOR RESPONSE FACTORS (F_{SO}, F_{ST})

3.1 DETAILED METHOD

3.1.1 METHOD OF ANALYSIS

As material properties of soil and structure, one hundred samples of shear velocity of soil and Young modulus of concrete are prepared respectively, which is distributed according to the average and the standard deviation specified beforehand. And by random sampling out of one hundred samples of shear velocity and Young modulus respectively, one hundred structual models are prepared. Then one hundred transfer functions of those structual models are computed by response analysis in frequency domain.

And then, using probabilistic distribution of seismic spectrum at the site and that of transfer function of structure, median and 84% non-exceedance value of maximum response values are culculated by the method of analysis which adopts the extreme-value theory based on the stationary random process and the random vibration theory (call it probabilistic theory method as follow).

By the extreme-value theory, standard diviation σ_x of amplitude under stationary Gauss process is related to maximum value of amplitude X_{max} through peak factor ν_p as expressed Eq. (6).

$$X_{max} = \nu_p \cdot \sigma_x \quad \cdots\cdots\cdots\cdots (6)$$

And by the random vibration theory, stationary response of vibrational system under stationary Gauss process can be expressed by transfer function and power spectrum of input as Eq. (7).

$$Sy(\omega) = [H(\omega)]^2 \cdot Sx(\omega) \quad \cdots\cdots\cdots\cdots (7)$$

where $Sx(\omega)$: input power spectrum

$Sy(\omega)$: response power spectrum

$H(\omega)$: transfer function of system

Namely, power spectrum of input, if obtained, combines with transfer function of structure settled by random sampling to form response power spectrum as above expressed Eq. (7). And then maximum response value of structure is obtained by considering peak factor as expressed Eq. (6).

Fig. 2 shows the calculation process of response factor based on detailed method as mentioned above, and Fig. 3 shows the calculation process of maximum Response value based on probabilistic theory Method.

3.1.2 THE ANALYSIS MODEL AND SEISMIC SPECTRUM

Fig. 4 shows the seismic analysis model of structure, and also in this figure, the specified floor for analysis in this paper is marked. The structual properties of design model (masses, shear sectional areas, moments of inertia) are taken as definite ones for the seismic analysis model.

Median and 84% non-exceedance value of real spectrum shape computed by seismic hazard analysis, and design spectrum shape at the site are as shown Fig. 1.

3.1.3 RESULTS OF ANALYSIS

Respective probabilistic distributions of Young modulus and damping factor of concrete for structure, and shear wave velocity for soil are specified, as shown Table 2, on the basis of the references and actural survey. It is assumed that these all probabilistic distributions are independant completely each other, but there is complete dependance between Young modulus and shear elastic modulus of concrete, and between shear wave velocity and damping of soil. And two probabilistic distributions for shear wave velocity of soil are there as horizontal stiffness and rotational stiffness respectively.

Fig. 5 shows histograms of material properties of concrete and soil which are created according to settled probabilistic distributions as shown Table 2. Broken lines in Fig. 5 mean specified probabilistic distributions. And Fig. 6 shows the results of transfer functions of one hundred analysis models of the structure between soil and the specified floor. Median and 84% non-exceedance value of those one hundred transfer functions are shown Fig. 7.

Median and 84% non-exceedance value of maximum response values are calculated by probabilistic theory method using seismic spectrum shapes as shown Fig. 1 and transfer functions as shown Fig. 7. And then considering these calculated values, by means of Eq. (3) and Eq. (4), median and 84% non-exceedance value of response factors are obtained as shown Table 1.

However respective values of F_{SO} and F_{ST} are not obtained but value of $F_{SO} \times F_{ST}$, because material properties of concrete and soil are varied simultaneously in this paper.

3.2 SIMPLE METHOD

3.2.1 METHOD OF ANALYSIS

Considering of uncertainty on material properties, probabilistic distributions of natural periods and modal dampings for structure are calculated. Then using seismic spectrum corresponding to median and 84% non-exceedance value of these calculated ones, median and 84% non-exceedance value of maximum response values are obtained by means of Eq. (8) and Eq. (9) as following expressed. Fig. 8 shows the relationships conceptually among probabilistic distributions of respective natural periods and modal dampings and seismic spectrum.

Precisely speaking, median of participation factors and eigen vectors vary according to material properties, but in this paper which are regarded as definite values.

$$R_{50} = \sqrt{\sum_{i}^{n} \left(\sum_{j}^{m} w_j \cdot \beta_i \cdot u_{ij} \cdot S_{i50} \right)^2} \quad \cdots\cdots (8)$$

$$R_{84} = \sqrt{\sum_{i}^{n} \left(\sum_{j}^{m} w_j \cdot \beta_i \cdot u_{ij} \cdot S_{i84} \right)^2} \quad \cdots\cdots (9)$$

where R_{50} : Median of Maximum Response Shear Force
R_{84} : 84% Non-Exceedance Value of Maximum Response Shear Force

i : Number of Degree (1, 2, ..., n) , j: Number of Floor (1, 2, ... , m)
w_j : Mass of jth Floor , β_i: Participation Factor of ith Degree
u_i : Eigen Vector of ith Degree
S_{i50} : Median of Seismic Spectrum corresponding to ith Degree
S_{i84} : 84% Non-Exceedance Value of Seismic Spectrum corresponding to ith Degree

3.2.2 THE ANALYSIS MODEL AND SEISMIC SPECTRUM

The same conditions of MCS method as described 3.1.2.

3.2.3 RESULTS OF ANALYSIS

Probabilistic distributions of natural periods and modal dampings are computed by eigenvalue analysis for the model with the same probabilistic distributions of material properties as prepared for MCS method. Then by means of Eq. (8), Eq. (9), and Eq. (3), Eq. (4), medians and 94% non-exceedance values of F_{SO}, F_{ST} are obtained as shown Table 1. Material properties of concrete and soil are varied simultaneously, so $F_{SO} \times F_{ST}$ are obtained.

4. COMPARISON OF THE RESULTS BY DETAILED METHOD AND SIMPLE METHOD

Comparing with response factors F_R obtained from both methods, median of simple method is 2.81 and detail method 3.84, namely simple method is about 70% for detailed method. This main reason is that SRSS method, which makes a rough calculation of maximum response, has a tendancy to give a large value to some extent generally compared with an accurate value. And also logarithmic standard deviation of simple method is smaller than that of detailed method, but the difference between both values is small.

Combining response factors as shown Table 1 with capacity safety factors obtained from another investigation, fragility curves are calculated as shown Fig. 9. According to this figure, peak ground acceleration at 50% probability of structural fragility is 5.2G by simple method and 7.1G by detailed method, that is, simple method is about 70% for detailed method. This main reason is also the same tendancy of SRSS method as above described.

5. CONCLUSIONS

Following conclusions are obtained from the results.

a) There are about 30% difference between the response factors obtained by simple method and by detailed method. But in bringing the order of probability into focus, the difference between both methods seems to be sufficiently small.
b) Fragility curve based on SRSS method gives more conservative results than detailed method one's, so SRSS method is available as simple method.

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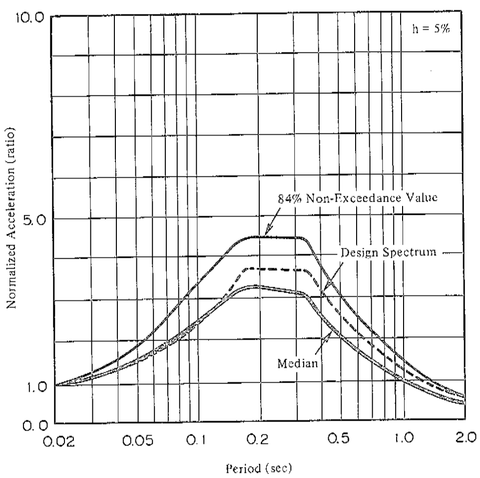

Fig. 1 Design Spectrum Shape and Real Spectrum Shape

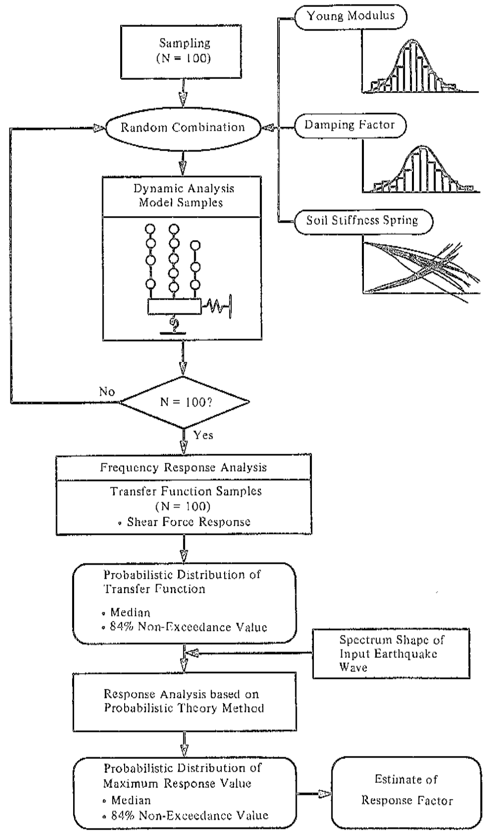

Fig. 2 Calculation Process of Response Factor based on Detailed Method

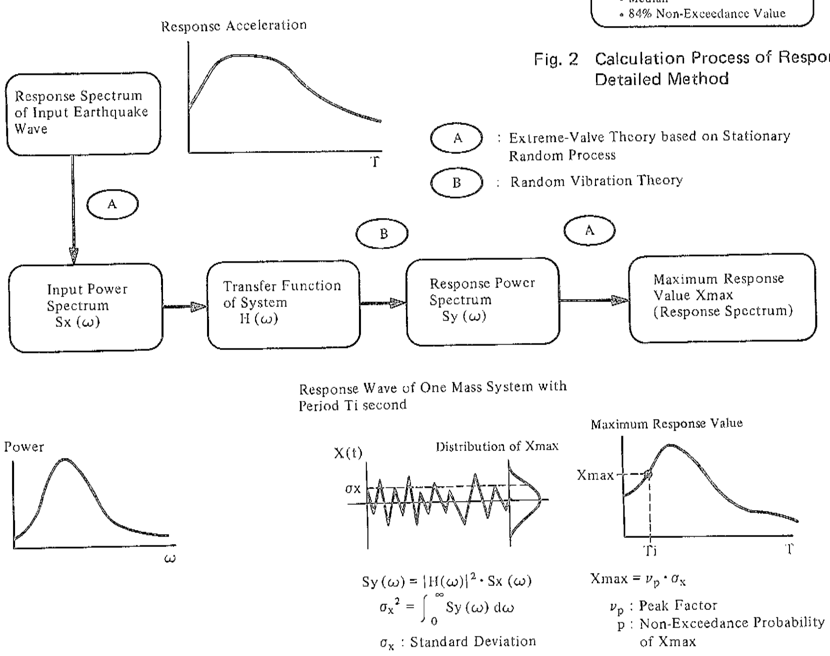

Fig. 3 Calculation Process of Maximum Response Value based on Probabilistic Theory Method

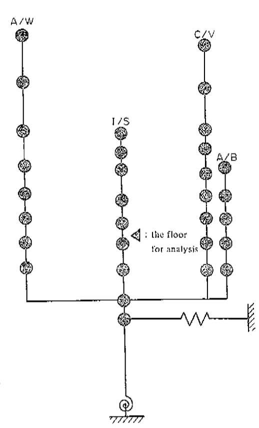

Fig. 4 Response Analysis Model

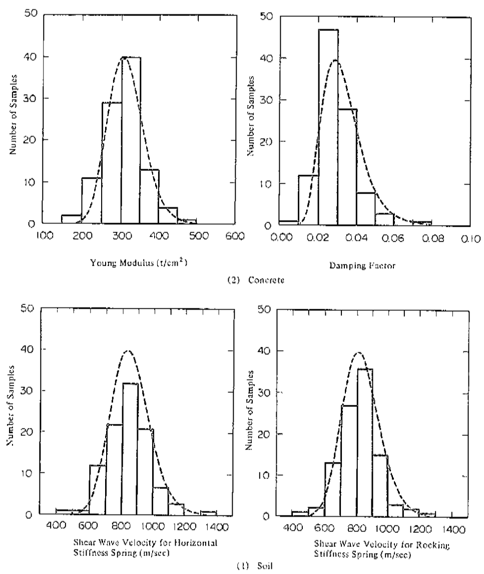

Fig. 5 Material Properties for Response Analysis Model (N = 100, Broken lines mean specified distributions as shown Table 2.)

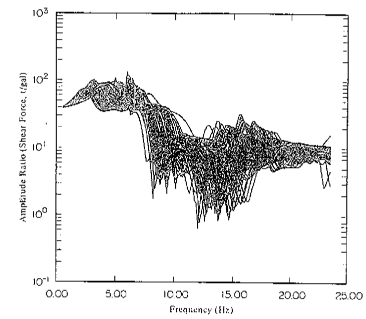

Fig. 6 Transfer Functions for Shear Force Response

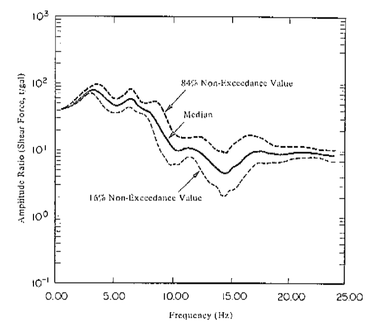

Fig. 7 Probabilistic Distribution of Transfer Function for Shear Force Response

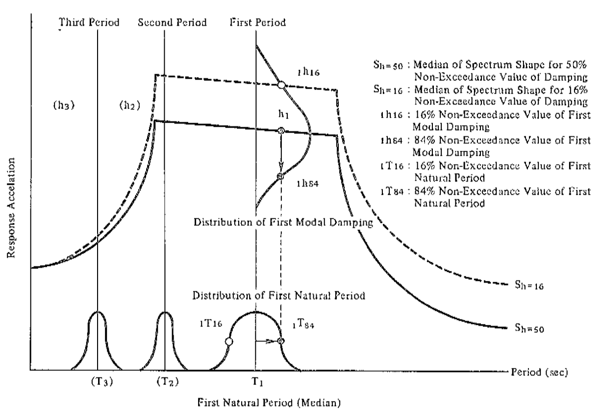

Fig. 8 Relationship among Distributions of Natural Periods, Modal Dampings and Response Spectrum

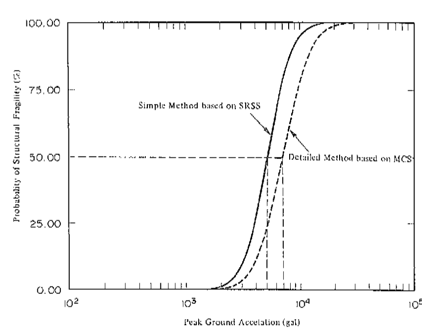

Fig. 9 Comparison of Fragility Curves

Table 1 Comparison of Response Factors

		F_{SA}	F_{SO}	F_{ST}	F_{MO}	F_R
Simple Method	Median	1.14	1.19		2.07	2.81
	βr	0.33	0.10		0	0.35
Detailed Method	Median	1.16	1.67		1.98	3.84
	βr	0.35	0.19		0	0.40

F_R (Median) = $F_{SA} \times F_{SO} \times F_{ST} \times F_{MO}$
βr (Logarithmic Standard Deviation) = $\sqrt{\Sigma \beta^2}$

Table 2 Probabilistic Distributions of Soil and Concrete for Material Properties

			Probabilistic Distribution	
			Average	Standard Deviation
Soil	Shear Wave Velocity	Horizontal*1	842 m/s	122 m/s
		Rocking*2	816 m/s	118 m/s
Concrete	Young Modulus		308 t/cm²	46 t/cm²
	Damping Factor		3%	1%

*1 for Horizontal Stiffness Spring
*2 for Rocking Stiffness Spring