A Study on the Applicability of the Response Estimation of Our PRA Procedure

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1 INTRODUCTION

The authors have been involved in development of structural response and fragility analysis techniques in a seismic PRA procedure adopted to the use in Japan. The basic simple procedure has been already established (Takeda et al., 1989) and it is now expected to be used in practice. However there still be a lot of uncertainties due to lack of knowledge and to the use of simplified methodology in the procedure. In this paper we report a study result on the applicability of the response estimation method of our seismic PRA procedure.

2 OUTLINE OF SELECTED BUILDING

We have selected a seven story building containing an electric substation for the surrounding area as a numerical example. The elevation of the building is shown in Fig. 1. The upper floors of the building are apartment houses and the electric substation is located on the base floors. Although this building is hypothetical, similar examples are popular in urban areas in Japan.

The building is assumed to be located in Odawara city, where a rather high seismicity is observed. The seismic hazard curve and the expected spectral shapes on the bedrock were evaluated for this location by Takemura et al. (1989). Response analysis is performed using a beam-mass model (Fig. 2). The properties of the response model are shown in Tables 1 and 2. The site condition and the soil properties are also shown in Fig. 1 and the soil nonlinearity is plotted in Fig. 3.

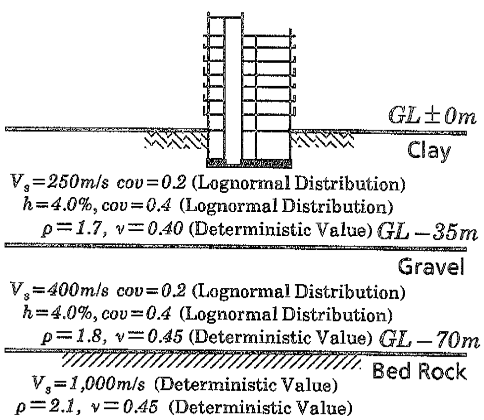

Figure 1. Site Condition

In this study, 3 failure modes are considered; the structural failure of the building, the functional failure of habitability and the functional failure of the electric substation. These modes are transformed to the criteria listed below, where the material properties are assumed as shown in Table 3.

1) The structural failure of the building is defined by the ultimate shear and bending deformation as Table 4.
2) The functional failure of habitability is expressed by the story drift limit of *1/200*.
3) The functional failure of the substation is assumed to occur due to the functional failure of switch board or mini clad or the overturning of transformer by failure of anchors.

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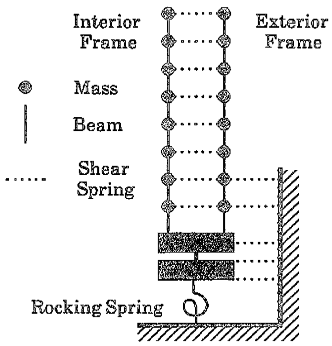

Figure 2. Response Model

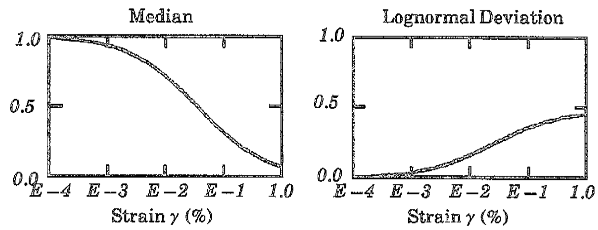

Figure 3. Soil Nonlinearity (G/G_0 vs γ)

Table 1. Properties of Masses of Analytical Model

Floor	Height (m)	Weight $(\times 10^3 kgf)$		In $(\times 10^5 kgfm^2)$	
		Exterior	Interior	Exterior	Interior
RF	22.6	442.6	774.9	29506.7	51660.0
7F	19.5	333.3	636.0	22220.0	42400.0
6F	16.4	345.5	657.5	23033.3	42833.3
5F	13.3	347.8	666.1	23186.7	44073.3
4F	10.2	357.3	678.6	23820.0	45240.0
3F	7.1	365.9	694.7	24393.3	46313.3
2F	4.0	414.3	783.1	27620.0	52206.7
1F	0.0	454.9	902.5	30326.7	60166.7
B1F	-4.0	424.5	656.1	28300.0	43740.0
B2F	-7.0	976.7		65113.3	
BM	-9.2	976.7		65113.3	

Table 2. Properties of Vertical Beams of Analytical Model

Floor	Section Area (m^2)		Inertia Moment (m^4)		Floor Spring
	Exterior	Interior	Exterior	Interior	(tf/cm)
RF	8.600	14.800	264.40	125.01	1600.0
7F	8.600	14.800	264.40	121.78	1600.0
6F	9.080	15.760	276.00	127.50	1600.0
5F	9.080	15.760	276.00	127.50	1600.0
4F	10.620	18.360	324.00	151.37	1600.0
3F	10.620	18.360	324.00	151.37	1600.0
2F	11.756	20.632	351.10	166.12	1600.0
1F	13.040	21.888	416.20	190.27	101600
B1F	14.680	21.888	480.70	191.98	100000
B2F					
BM	36.568		672.68		

$E=250.0tf/m^2$, $\beta_E = 0.1$, $h=0.05$, $\beta_h=0.51$

Table 3. Properties of Materials

	Compressive Strength $(kgf/cm2)$	Yield Stress $(kgf/cm2)$	
	Concrete	Reinforcing Bar	Anchor
Median	362.90	4200.0	4920.0
Lognormal Deviation	0.14	0.05	0.05

Table 4. Ultimate Ductility Factor of RC Members

	Shear	Bending
Median	4.00	12.00
Lognormal Deviation	0.15	0.20

3 OUTLINE OF OUR SEISMIC PRA PROCEDURE

Fig. 4 shows the flow chart of our seismic PRA procedure for the failure of the structure, reported by Takeda et al.(1989). The particular features are;

1) Damage concentration effect of Multi Degrees of Freedom (MDOF) systems is considered.
2) Responses are evaluated applying stationary random theory.
3) Soil-Structure interaction effects are properly considered in the response analysis model
4) Expected response spectral shape of input motion is defined by the median shape and the *84%* non-exceedant shape (two points estimation).
5) Expected transfer function of the system is expressed by the median value and the *84%* non-exceedant value (two points estimation).
6) Soil nonlinearity is considered.

Fig. 5 shows the image of our procedure for the failure of equipment. The capacity of the equipment is expressed by the Test Response Spectra (TRS: Brookhaven National Lab., 1987). This report contains the result of a series of shaking table tests of several equipment items together with the input motion spectral shapes and the descriptions on the failure of these items. The authors estimate the corresponding median values and lognormal standard deviations of the capacity of the equipment according to these descriptions.

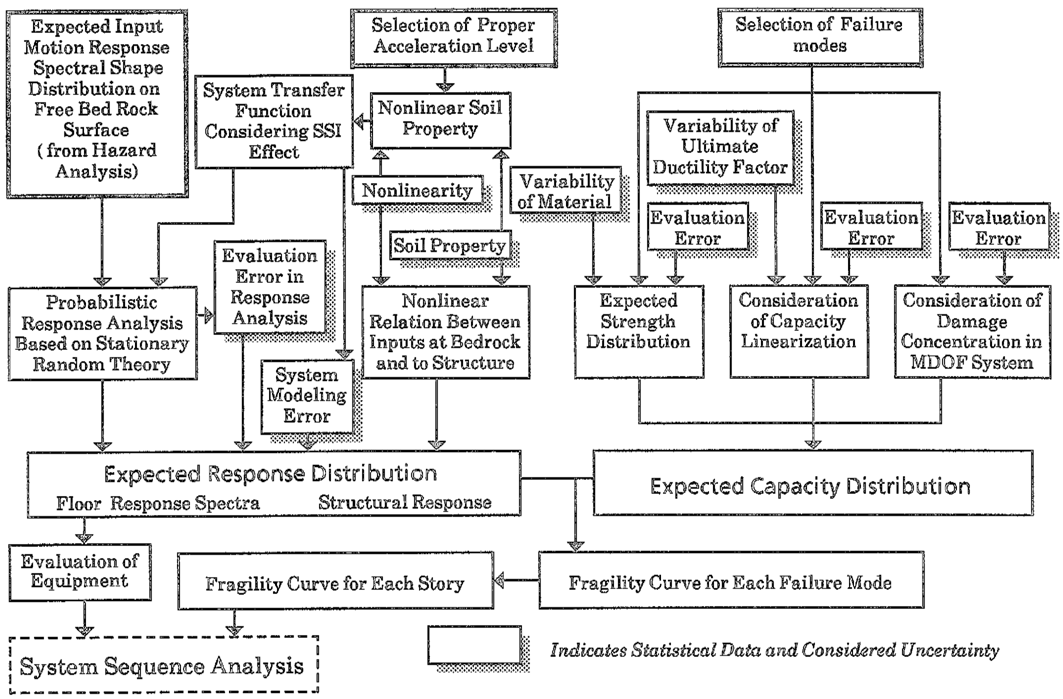

Figure 4. Flowchart of Evaluation Method (Structure)

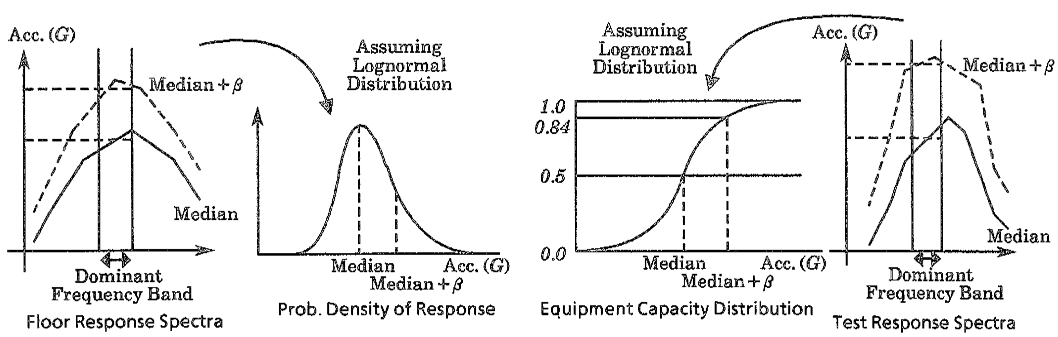

Figure 5. Functional Fragility Evaluation Method of Equipment

4 EVALUATION RESULTS

The seismic hazard curve and the input response spectral shapes at Odawara have been evaluated and reported (Takemura et al., 1989, Fig. 6 and 7). Fig. 5 shows the relationship between the input motion at bedrock surface and the input motion to the building accounting for soil nonlinearity. Table 5 and Fig. 8 show some estimated results of response when the input acceleration level is *800* cm/s^2. Fig. 9 shows the fragility curve for each failure mode. The annual failure probabilities calculated with the seismic hazard curve and fragility curves are presented in Fig. 10.

Table 5. Expected Response Moment

Floor	Exterior Wall							Interior Wall						
	R_{50} (*tfm*)	F_1 β_r	F_2 β_r	F_3 β_u	F_4 β_u	R(*tfm*) β_r	R(*tfm*) β_u	R_{50} (*tfm*)	F_1 β_r	F_2 β_r	F_3 β_u	F_4 β_u	R(*tfm*) β_r	R(*tfm*) β_u
7F	2.82×10^5	1.00	1.00	1.00	1.00	2.82×105		3.63×10^5	1.00	1.00	1.00	1.00	3.63×105	
		0.27	0.70	0.30	0.15	0.75	0.34		0.24	0.83	0.30	0.15	0.87	0.34
4F	2.29×10^6	1.00	1.00	1.00	1.00	2.29×106		1.56×10^6	1.00	1.00	1.00	1.00	1.56×106	
		0.30	0.69	0.30	0.15	0.75	0.34		0.27	0.72	0.30	0.15	0.77	0.34
1F	5.23×10^6	1.00	1.00	1.00	1.00	5.23×106		3.33×10^6	1.00	1.00	1.00	1.00	3.33×106	
		0.31	0.69	0.30	0.15	0.76	0.34		0.30	0.68	0.30	0.15	0.74	0.34
B2F	6.01×10^6	1.00	1.00	1.00	1.00	6.01×106		3.07×10^6	1.00	1.00	1.00	1.00	3.07×106	
		0.34	0.74	0.30	0.15	0.82	0.34		0.37	0.83	0.30	0.15	0.90	0.34

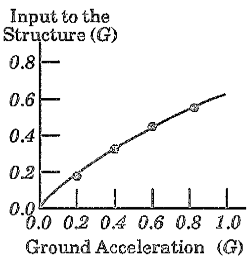

Figure 5. Input Motion Nonlinearity

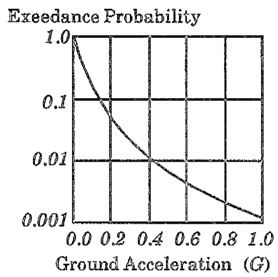

Figure 6. Seismic Hazard Curve

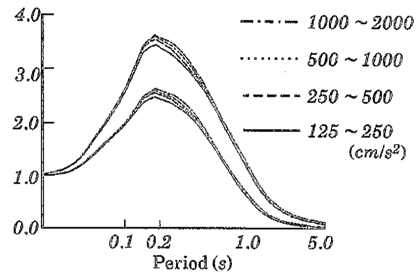

Figure 7. Expected Input Response Spectral Shapes

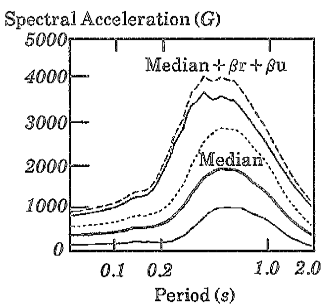

Figure 8. Expected Floor Response Spectrum

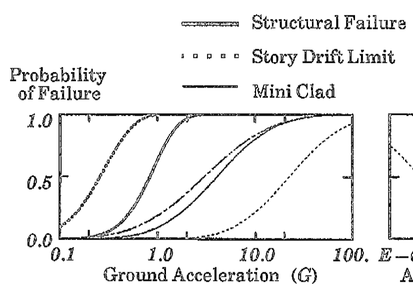

Figure 9. Fragility Curves

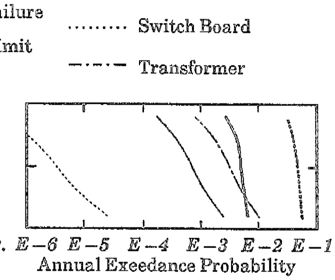

Figure 10. Failure Frequency

5 MONTE CARLO SIMULATION

A Monte Carlo simulation is conducted in order to investigate the applicability of the response estimation method of our PRA procedure. Table 6 shows the difference between our PRA procedure and the Monte Carlo simulation. The total size of the Monte Carlo simulation is 100. Table 7 and Fig. 11 show some of results. Fig. 12 shows failure probabilities of a mini clad and a transformer. The median failure probability of the mini clad is $p_f=0.070$ by our procedure at input level *800 cm/s²* and $p_f=0.107$ by the Monte Carlo simulation. The median failure probability of the transformer is $p_f=0.151$ by our procedure and $p_f=0.101$ by the Monte Carlo.

The evaluated floor response spectrum differs a little from one by our procedure. However in the period range longer than *0.4 sec.*, both the median and the variation are much the same. The failure probability becomes smaller as the median value of the response becomes smaller and becomes larger as the variation of the response becomes larger. In our procedure, the median of the response is estimated smaller and the variation of the response is estimated larger than those by the Monte Carlo simulation and this leads to the resultant failure probabilities about the same for both results.

Table 6. Comparison of the Monte Carlo Simulation and Our PRA Procedure

		Our PRA Procedure	Monte Carlo Simulation
System	Input Motion	Median and 84% Non-exeedance Value	Generate 100 Samples
	Structure	Generate 100 Samples	Generate 100 Samples
	Transfer Function and Impedance of Soil	Generate 100 Samples	Generate 100 Samples
	System Transfer Function	Median and 84% Non-exeedance Value	100 Transfer Functions
Response Analysis		Stationary Random Theory	Analysis in Time Domain
Capacity	Mini Clad	Median and Log-normal Deviation of TRS	Median and Log-normal Deviation of TRS
	Failure of Anchor	Median and Log-normal Deviation of Capacity of Anchor	Median and Log-normal Deviation of Capacity of Anchor
	Fragility	Average Value of Response and Capacity in Major Period Band of Equipment	Based on 100 Samples in Major Period Band of Equipment

Table 7. Expected Response Moment

Floor	Our PRA Procedure				Monte Carlo Simulation			
	Exterior Wall		Interior Wall		Exterior Wall		Interior Wall	
	R(*tfm*)	β_r	R(*tfm*)	β_r	R(*tfm*)	β_r	R(*tfm*)	β_r
7F	2.82×10^5	0.75	3.63×10^5	0.87	3.62×10^5	0.54	4.82×10^5	0.59
4F	2.29×10^6	0.75	1.56×10^6	0.77	2.93×10^6	0.55	2.01×10^6	0.54
1F	5.23×10^6	0.76	3.33×10^6	0.74	6.72×10^6	0.56	4.25×10^6	0.54
B2F	6.01×10^6	0.82	3.07×10^6	0.90	7.96×10^6	0.61	4.27×10^6	0.64

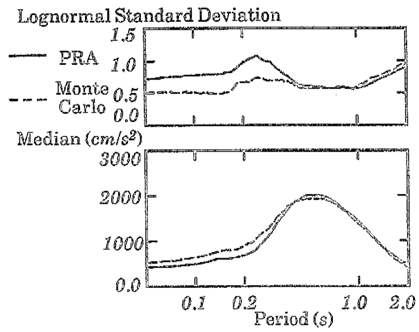

Figure. 11 Expected Floor Response

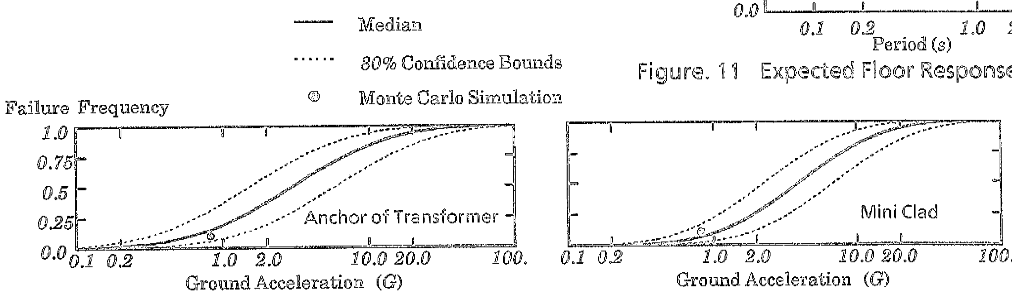

Figure. 12 Comparison of Failure Frequencies

6 CHARACTERISTICS OF OUR SEISMIC PRA PROCEDURE

In this section, the characteristics of our procedure are discussed. The issues are listed below and the response spectrum at basement 2F is studied.

1) Response evaluation using stationary random theory.
2) Two points estimation of expected response spectral shape of input motion.
3) Two points estimation of expected system transfer function.

The parameters taken into consideration are summarized in Table 8. Case 1 corresponds to the previous Monte Carlo simulation. Case 5 corresponds to our PRA procedure. Cases 2, 3 and 4 are introduced to study the characteristics of three simplified features in our PRA procedure.

Fig. 13 (a), comparing cases 1 and 2, shows that the response analysis using stationary random theory gives larger values both for the median and the variation than those by the time domain analysis. The difference is less than *10%*. Fig. 13 (b) compares cases 2 and 3, and cases 4 and 5. Two points estimation of expected input motion response spectral shape makes underestimation both for the median and the variation. The difference of the median values is about *10%*. The difference of variations is *5%* around the period of *0.3 sec.* and grows up to *25%* in the longer period range. In Fig. 14 the variations of response spectra due to variability of input motion calculated by our procedure and by the Monte Carlo simulation are compared.

Fig. 13 (c) compares cases 2 and 4, and cases 3 and 5. The use of two points estimation of expected system transfer function underestimates the median value in shorter period range than *0.2 sec.* where the difference is around *20%*, but it tends to decrease in longer period portion. The variation derived by the two points estimation is about *50%* higher than that by the Monte Carlo simulation in the period shorter than *0.3 sec.* and *20%* higher in the longer period range. Fig. 15 compares the variances of response spectra due to the variability of transfer function. In this case, our PRA procedure gives larger variance.

Table 8. Case Summaries

Case	Response Evaluation	Statistic Characteristics of Input Motion	Statistic Characteristics of Transfer Function
1	In Time Domain	Monte Carlo Simulation	Monte Carlo Simulation
2	Stationary Random Theory	Monte Carlo Simulation	Monte Carlo Simulation
3	Stationary Random Theory	Two Points Estimation	Monte Carlo Simulation
4	Stationary Random Theory	Monte Carlo Simulation	Two Points Estimation
5	Stationary Random Theory	Two Points Estimation	Two Points Estimation

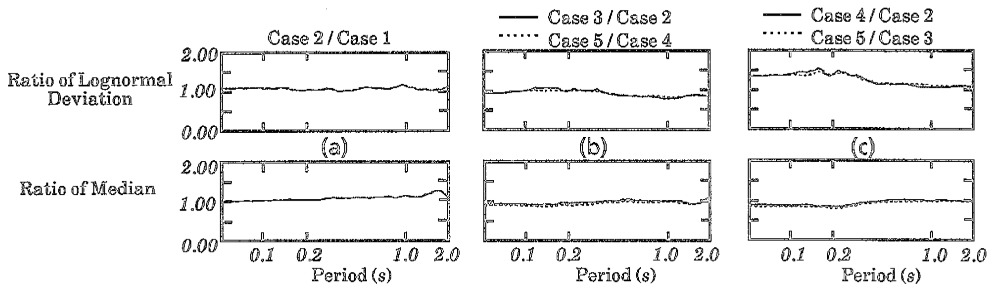

Figure 13. Comparison Between Cases

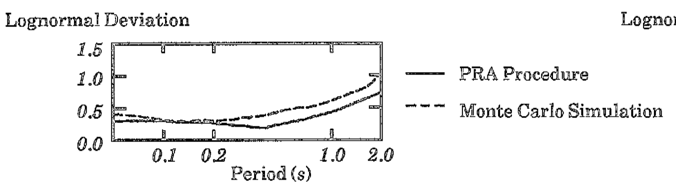

Figure 14. Variance of Response Spectra due to Variability of Input Motion

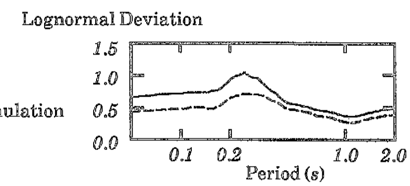

Figure 15. Variance of Response Spectra due to Variability of Transfer Function

7 CONCLUSION

A PRA procedure for the structural and the functional failures of buildings is illustrated and the applicability was studied through the comparison with the results of a Monte Carlo simulation. In our procedure, several approximations are used and each of them causes incorrect evaluation to some extents. However, our procedure will give adequate results as a whole. Hence, it is concluded that our seismic PRA procedure can stand for a simplified evaluation method.

REFERENCES

Broockhaven National Laboratory (1987), Seismic Fragility of Nuclear Power Components (Phase 2).

Takeda, M., Kai, Y., Mizutani, M. (1989), A Seismic PRA Procedure in Japan and its Application to a Building Performance Safety Estimation Part 2 Fragility Analysis, ICOSSAR. Vol. 1 pp. 629-636

Takemura, M. et al. (1989), A Seismic PRA Procedure in Japan and its Application to a Building Performance Safety Estimation Part 1 Seismic Hazard Analysis, ICOSSAR.Vol. 1 pp. 621-628