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RELIABILITY ENHANCEMENT OF SEISMIC RISK ASSESSMENT OF NPP AS RISK MANAGEMENT FUNDAMENTALS PART III: SENSITIVITY ANALYSIS FOR THE QUANTIFICATION OF EPISTEMIC UNCERTAINTY ON FRAGILITY ASSESSMENT

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ABSTRACT

This study focused on uncertainty-assessment frameworks, the utilization of expertise, and the development of relevant software to improve the reliability of seismic probabilistic risk assessment (SPRA) and promote its further use. In addition, a methodology was developed for quantifying the uncertainty associated with the final SPRA results within the risk management framework of nuclear power plant facilities. This research aimed at contributing to (1) the development of probabilistic models for uncertainty quantification and software, (2) the aggregation of expert opinions on structure fragility estimation and development of implementation guidelines on epistemic uncertainty, and (3) the study of the applicability of newly proposed SPRA models to plant models. In particular, we focused on the second goal.

Two different groups of experts, those in the field of civil engineering and those in the field of mechanical engineering, were consulted in the study. With these groups, we conducted a pilot study on the use of expert-opinion elicitation for the identification and quantification of fragility assessment parameters. Some sensitivity analyses were performed using a three dimensional reactor-building model and a conventional evaluation model, and the results were provided to the experts for expert-opinion elicitation. The results of the sensitivity analyses were related to the uncertainty evaluation of the buildings and soil to evaluate the fragility of the equipment. In this paper, those results will be shown in comparison with a conventional evaluation model.

INTRODUCTION

Seismic safety is evaluated by quantifying and identifying the various uncertainties in probabilistic seismic risk evaluation of nuclear power plant (NPP) facilities. The level 1 Probabilistic Risk Assessment (PRA) is performed in three distinct steps while paying attention to the interface between each step: (1) onsite seismic hazard evaluation, (2) fragility evaluation of buildings and equipment, and (3) accident sequence analysis (AESJ (2007)). For the evaluation process, uncertainty is classified into aleatory uncertainty (i.e., randomness) and epistemic uncertainty (i.e., lack of knowledge). Upon evaluation, these uncertainties are generally quantified based on engineering judgment and experience, due to lack of data. We especially emphasize the importance of epistemic uncertainty.

The Senior Seismic Hazard Analysis Committee's (SSHAC) method (USNRC (1997, 2012)) for earthquake hazard assessment was proposed and implemented in the United States. This method employs a graded approach, which considers the difficulty, complexity, and significance of results from hazard evaluation of target sites. For the most in-depth evaluation, a logic tree is adopted to summarize different opinions on serious subjects obtained from multiple experts, in addition to relevant literature review.

Fragility evaluation of buildings and equipment is divided into two parts: (1) response evaluation of the soil, buildings, and equipment in the upper region of the engineering-base surface, and (2) strength evaluation associated with damage modes of buildings and equipment components. In this study, we performed an assessment of the uncertainty in the seismic response evaluation of soil in the upper region of the engineering-base surface, of the uncertainty of inputs to the reactor building, and of the uncertainty in response evaluation of buildings and equipment.

Epistemic uncertainty with regard to fragility analysis is assessed by applying the knowledge of experts, in order to identify the sources and ranges of uncertainty. This assessment process improves the credibility of fragility analysis. Because the SSHAC method of using expert-opinion consultation was developed for earthquake hazard assessment, this is the first time they were applied to fragility evaluation in Japan. Specialized knowledge obtained during the process is adjusted and integrated by using a logic tree to categorize important subjects.

We performed sensitivity analyses for some analytical parameters according to the subjects provided by experts. A conventional reactor building model (SR model) and a three dimensional reactor-building model were constructed and used for the sensitivity analysis. The results were also provided to the experts for expert-opinion elicitation. These processes were carried out repeatedly. The results of sensitivity analyses were considered with the epistemic uncertainty evaluation of the buildings and soil to evaluate the fragility of the equipment. In this research, the uncertainty is evaluated as a variation against the SR model.

In this paper, those sensitivity analytical results and a trial evaluation of the uncertainty by using the analytical results will be shown in comparison with the SR model. Finally, the sensitivity analytical results obtained in this study will be included as a part of a proposed guideline for treatment of epistemic uncertainty using the knowledge obtained in this study.

OUTLINE OF A BASIC MODEL FOR EXPERT-OPINION ELICITATION

Our main target is earthquake response analysis using the Sway-Rocking (SR) model shown in Figure 1, which is a standard model used in the fragility analysis of buildings and equipment. In particular, we focused on the uncertainty of one-dimensional wave propagation theory (i.e., equivalent to linear analysis), indispensable for soil analysis. Furthermore, to obtain unbiased opinions from experts, we selected a concrete case-study site and model plant to present to them beforehand. The information presented consisted of case-study site information, uncertainty-research results, and an example of response analysis of the selected model plant. The Peak Ground Acceleration (PGA) of input ground motions is assumed to be twice that of “Ss,” which is the basic earthquake ground motion for seismic assessment of NPP in Japan. We anticipate that the building will respond in a near-linear manner and that part of the soil will respond nonlinearly under these conditions.

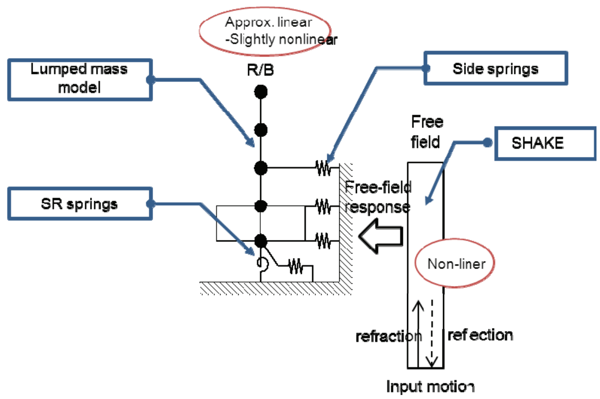


Figure 1. Profile of Embedded SR (Sway-Rocking) Model.

OUTLINE OF SENSITIVITY AND RESPONSE ANALYSIS FOR EXPERT-OPINION ELICITATION

We performed sensitivity and response analysis by using a constructed, embedded SR model and a three-dimensional (3D) model to provide experts with results for expert-opinion elicitation. Deliverables of our research are a selection guide of uncertainty factors and a comprehensive report of the range of uncertainties investigated in the response analysis. Response and sensitivity analysis of target buildings and soil of the model plant are carried out with the aim to provide information to experts, facilitating assessment of epistemic uncertainty in the response evaluation of fragility analysis of equipment by expert-opinion elicitation. In this section, we summarize the reactor-building modeling, results of the eigenvalue analysis, and comparisons of analytical results and observed seismic-response records, carried out to validate the model.

SELECTION OF MODEL PLANT

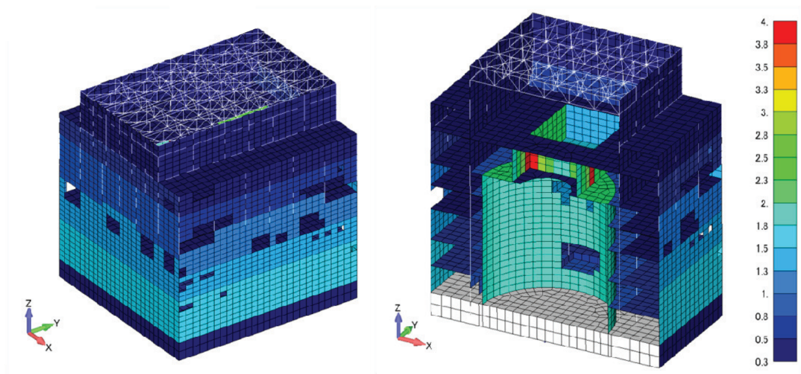
To survey available plant information and observed earthquake data to construct a reactor-building model, we collected public information on light-water reactor buildings from the Japan Nuclear Energy Safety (JNES) library and the Nuclear and Industrial Safety Agency (NISA) (Seismic design standards subcommittee for LWR improvement (1981), JNES). Additionally, we obtained information from the KARISMA benchmark (IAEA), which was carried out by the International Atomic Energy Agency (IAEA) over a period of five years from 2008 until 2013. We decided to become a member of the KARISMA benchmark and received access to the plant's information about the KARISMA benchmark. Then, we constructed an analytical model of the plant by using the information of the KARISMA benchmark. Because the obtained data only provided us with part of the required information and were insufficient to create a full model of the target-reactor building, we were forced to supplement the model with publicly available information (TEPCO (2009, 2008), Fukuwa (2009), Hijikata et al (2011))

SUMMARY OF REACTOR-BUILDING MODELING

The SR model and the three-dimensional FEM model were created in order to perform the sensitivity analysis. Sensitivity analysis would primarily be performed by using the SR model, though the analysis of the three-dimensional FEM model would also be performed for verification of the results of the SR model. The SR model was created based on public information and literature and confirmed to be consistent with the results. In this section, we summarize the construction of the 3D FEM model.

Construction of the Finite Element Method (FEM) Model

As a first modeling step, the 3D shape model was created using 3D Computer Aided Design (CAD) software. We created the FEM model based on 3D shape model. The FEM model consisted of shell elements, solid elements, and truss or beam elements. We used shell elements for walls and slabs and solid elements for foundation slab. The model consisted of 14,334 elements, 11,796 nodes, with about 64,000 degrees of freedom. Additionally, to determine the weight inputs of the FEM model, the volumes of the columns, beams, walls, and floors were calculated. We defined the mass density of each floor of the FEM model such that the total mass of each floor matched that of the SR model. Figure 2 shows the FEM model of the reactor building.



(a) (b)

Figure 2. FEM Model of Reactor-Building Model (color ramp indicates thickness of each element in meters): (a) Bird's-Eye View and (b) Cross-Sectional View.

We selected walls for 3D modeling of the plant building according to the references. Material properties of the roof truss and building are shown in Table 1. The properties of the SSI springs of the FEM model were determined by referencing the SR model of the KARISMA benchmark. The springs were arranged in the FEM model by distributing the springs of the SR model along the interacting surfaces of the wall or the base mat. The locations of the SSI spring are shown in Figure 3.

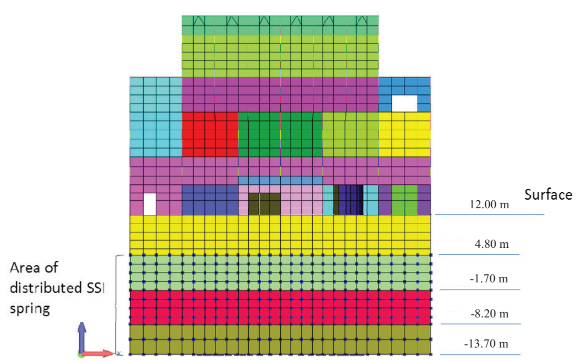


Figure 3. Setting of SSI Springs.

Table 1: Material Properties of Roof Truss and Building.

Component	Material	Young's modulus (kN/m^2)	Poisson's ratio	Mass density (kg/m^3)	Dumping constant: h
Roof truss	Steel	2.05 E+08	0.3	77.0	0.02
Building	Concrete	3.13 E+07	0.2	25.0	0.05

SEISMIC WAVES FOR ANALYSIS

The input seismic waves for sensitivity analysis are shown in Figure 4. Input seismic wave A was generated using a fault model and it has three components: east/west (EW), north/south (NS), and up/down (UD); whereas input seismic wave B was generated from spectral waves and it has two components: horizontal and vertical. The maximum accelerations of input seismic waves A and B are shown in Table 2.

Table 2: Maximum Acceleration of Input Seismic Waves.

Input seismic wave	Horizontal direction		Vertical direction
	EW	NS	UD
A	1209	-848	466
B	-600		-400

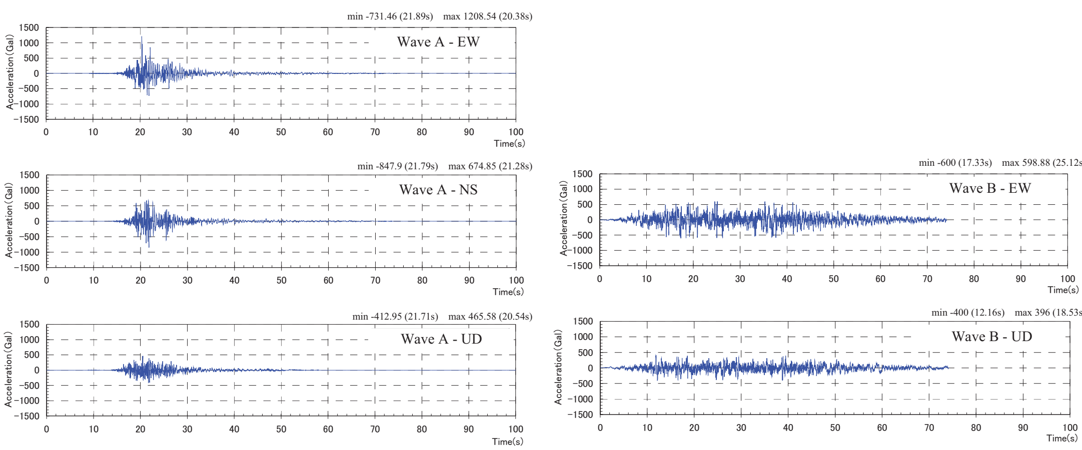


Figure 4. Input Seismic Waves.

VALIDATION OF THE ANALYTICAL MODEL

Eigenvalue Analysis

To validate the constructed analytical models, an eigenvalue analysis was performed, and the results of the FEM and SR models were compared. The obtained natural modes for the FEM and SR models are shown in Figures 5 and 6, respectively. These figures show the first and second order natural modes of the NS direction of the building. Furthermore, the obtained natural frequencies are shown in Table 3. Table 3a shows the analytical results of the FEM model, and Table 3b shows the analytical results of the SR model. The first and second modes are the primary modes because the sums of the effective mass ratio of these two modes for the SR model and FEM model are 93.9% and 99.6%, respectively.

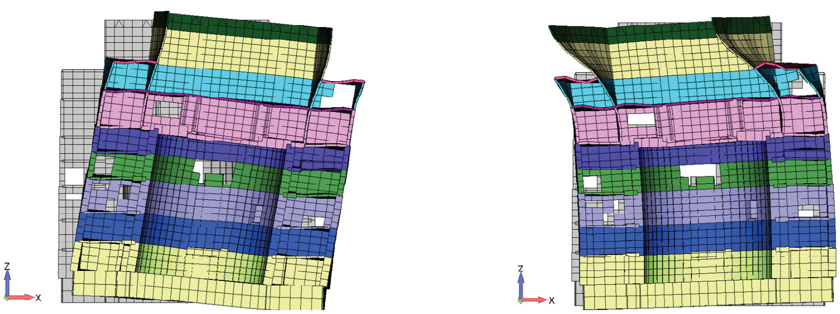
Table 3: Natural Frequencies (NS) of (a) the FEM and (b) the Embedded SR Model.

(a)

Mode	Natural Frequency (Hz)	Natural Period (s)	Effective Mass Ratio	
			X	Z
1 (16)	2.268	0.441	0.778	0.000
2 (34)	5.158	0.194	0.161	0.000
3 (47)	6.200	0.161	0.047	0.002
4 (69)	9.318	0.107	0.005	0.001

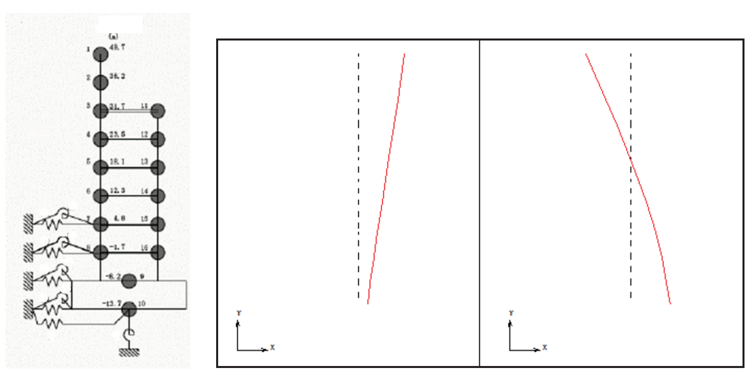
(b)

Mode	Natural Frequency (Hz)	Natural Period (s)	Effective Mass Ratio	
			X	RZ
1	2.278	0.439	0.756	0.096
2	5.172	0.193	0.240	0.354
3	11.52	0.087	0.000	0.003
4	13.40	0.075	0.000	0.206



(a) (b)

Figure 5. Natural Modes of the FEM Model (NS): (a) Mode16 = 2.268 Hz and (b) Mode 34 = 5.158 Hz.

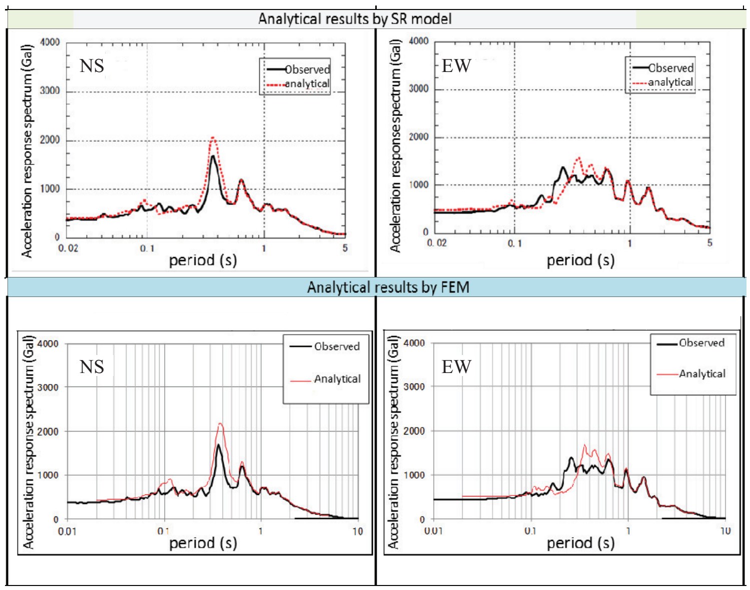


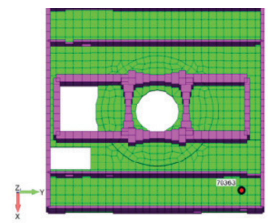
(a) (b) (c)

Figure 6. Embedded SR Model (TEPCO (2009)) (a) and its Natural Modes (NS): (b) Mode 1 = 2.278 Hz and (c) Mode 2 = 5.172 Hz.

Comparison with Observed Earthquake Data

To validate the constructed FEM model, we compared the analytical results to earthquake data; these are shown in Figure 7. The horizontal axes show periods (in seconds) and the vertical axes show the acceleration response spectrum (in gals). The black and red lines indicate observed and analytical results, respectively.





Output Positions of
Analytical Results

Figure 7. Observed and Analytical Acceleration Response Spectrum on the Third (Middle) Floor for the SR Model (Top)[9] and the FEM Model (Bottom).

These results show that observed and analytical results are largely consistent. However, the observed spectrum in the EW direction between 0.2 and 0.3 seconds is not reproduced in the analytical results. Because a deliverable of this study is a selection guide of uncertainty factors and ranges for response analysis, and not a simulation of observed data, we decided that the results were sufficiently accurate to use this model to perform sensitivity analysis.

Response Differences on the Same Floor

Figure 8 shows the results of a pre-study on sensitivity analysis to investigate the influence of equipment positioning on floor response. To explore relationships between the input and the responses, the responses of the three directions to the analytical input are investigated. The results are shown as acceleration transfer functions. For example, the upper three figures in Figure 8 show the responses of a slab in the EW, NS, and UD directions, to the input in the EW direction. The horizontal axis shows frequency (in Hz) and the vertical axis shows the acceleration transfer functions (in dimensionless quantity). The three diagonal figures show the responses in the EW, NS, and UD directions for the inputs in the EW, NS, and UD directions, respectively. The lines of different color show responses at different points on the same floor. We can infer that differences in response amplitude occur on the same floor, and that differences are larger in the high-frequency region. Furthermore, the response amplitude tends to be larger at the end of the opening compared to the other points.

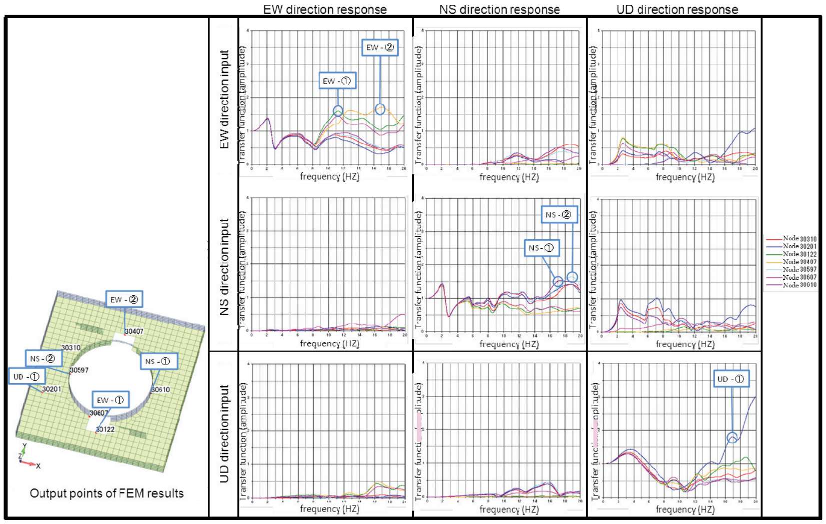


Figure 8. Amplitude of Acceleration Transfer Function for Each Direction.

SENSITIVITY ANALYSIS

Uncertainty Parameters used in the Sensitivity Analysis

Table 4 shows the uncertainty parameters used in the sensitivity analysis. The FEM model will be used for parameters one through seven. The SR model will be used for parameter eight, as it relates to soil-properties. A literature survey will be performed for parameters nine and ten.

Table 4: Uncertainty Parameters Used in the Sensitivity Analysis.

S. No.	Parameters	Method
1	Modeling area (quake-resistant wall, non quake-resistant wall, opening part of wall/slab, steps, non-structural member, etc.)	FEM model
2	Modeling errors (mesh size, error of center axis, etc.)	FEM model
3	Interaction between heavy equipment and building	FEM model
4	Influence of rigid/non-rigid floor assumption	FEM model
5	Influence of rigid/non-riged base mat	FEM model
6	Influence of input wave (3D input, 1D input, etc.)	FEM model
7	Soil-structure interaction (join condition of soil-base wall or soil-side wall, etc.)	FEM model
8	Consideration of non-linearity of soil, building structure, soil-building structure, etc.	SR model
9	Interaction between adjoining buildings	Literature survey
10	Material property (stiffness, strength, dumping of concrete, etc.)	Literature survey

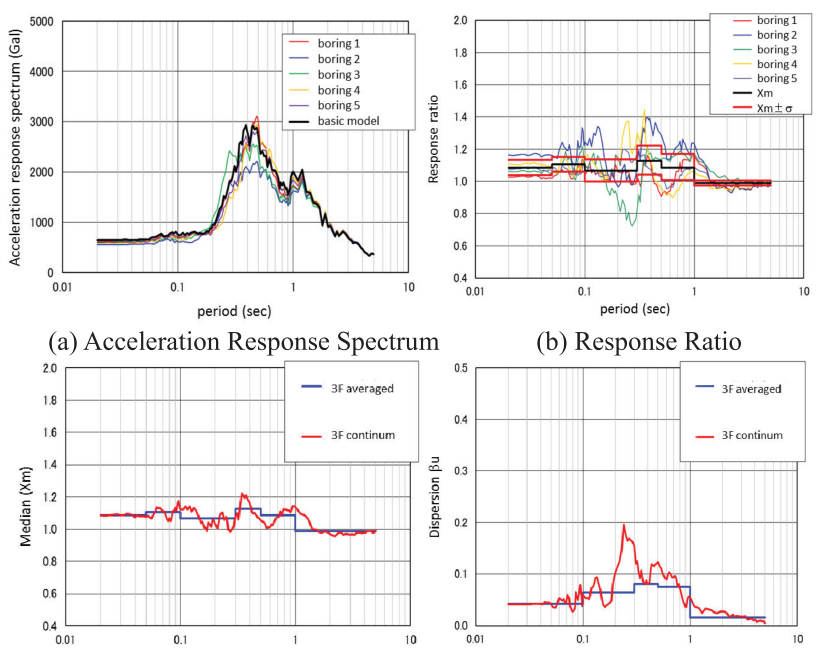
Results of Sensitivity Analysis

Table 5 shows an example of the uncertainty evaluation for parameter eight (soil properties). Four kinds of parameters were selected: material property of soil, backfill soil, boundary condition at base mat and side wall, and nonlinear effect of soil. The response ratios were calculated relative to the basic SR model.

Figure 9 shows an example of uncertainty evaluation for the material property of soil: (a) the acceleration response spectrum (h=3%) on the 3rd floor, (b) the response ratio based on the basic SR model, (c) the median X_m of the response ratio, (d) and the dispersion β_u of the response ratio. The dispersion is shown as the logarithm of the standard deviation. In this case, dispersion values are lower than 0.1, and the total dispersion of these soil properties is also lower than 0.1.

Table 5: A Trial of Uncertainty Evaluation for Four Kinds of Soil Parameters (Input Wave A).

Period (s)	**Material Property of Soil**		**Backfill Soil**		**Boundary Condition at Base Mat and Side Wall**		**Nonlinear Effect of Soil**	
	Median X_m	β_u ζ	Median X_m	β_u ζ	Median X_m	β_u ζ	Median X_m	β_u ζ
0.02-0.05	1.085	0.043	1.022	0.011	1.013	0.003	1.039	0.027
0.05-0.10	1.105	0.042	1.065	0.000	1.068	0.003	1.043	0.022
0.10-0.30	1.066	0.064	1.079	0.072	1.005	0.002	1.011	0.007
0.30-0.50	1.127	0.080	1.145	0.070	1.070	0.002	1.041	0.025
0.50-1.00	1.086	0.075	0.989	0.054	1.043	0.001	1.083	0.037
1.00-5.00	0.990	0.016	1.005	0.004	1.009	0.000	1.008	0.001



(a) Acceleration Response Spectrum (b) Response Ratio
(c) Median of Response Ratio (d) Dispersion of Response Ratio

Figure 9. Example of Uncertainty Evaluation with the Median and Dispersion for Material Property of Soil.

CONCLUSIONS

Based on the one-dimensional wave theory, essential to seismic response analysis of buildings and equipment, and the conventional SR model, we have attempted to obtain opinions on high-impact factors from experts to reduce epistemic uncertainty through expert-opinion elicitation. Furthermore, we were able to confirm the relevance of the proposed factors in the sensitivity analysis.

Finally, ten parameters were selected for the sensitivity uncertainty parameters. In preparation for the sensitivity analysis of target buildings and ground of the model plant, a reactor-building model was created, the validity of which we confirmed by comparing observed records to analytical results and by performing eigenvalue analysis. We performed sensitivity analyses related to the uncertainty evaluation of buildings and soil, for the purpose of fragility evaluation of equipment by using the present model. The analytical results were compared to the conventional SR model. Evaluated uncertainties were almost lower than 0.1 and those values are approximately equal to the value shown in the seismic PRA standard published by AESJ.

For future work, we are planning to continue to perform sensitivity analyses and to map out uncertainties using a logic tree. Additionally, we found that seismic-safety evaluation is subdivided into many technical fields and identified this as an issue in this study; therefore, we are planning to strengthen the cooperation between these fields in the future.

ACKNOWLEDGEMENTS

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