Reliability Enhancement of Seismic Risk Assessment of NPP as Risk Management Fundamentals
-Quantifying Epistemic Uncertainty in Fragility Assessment Using Expert Opinions and Sensitivity Analysis-

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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 facilities. This research aimed at contributing to the aggregation of expert opinions on structure fragility estimation and development of implementation guidelines on epistemic uncertainty. There are two expert groups formed in this study: experts in the field of civil engineering (CE experts) and those in the field of mechanical engineering (ME experts). We conducted a pilot study with these groups on the use of expert opinions elicitation for the identification and quantification of fragility assessment parameters. Also, 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 opinions elicitation. Epistemic uncertainty relevant to fragility analysis is assessed by systematically eliciting knowledge of experts, in order to identify the sources and ranges of uncertainty. Through this assessment process, credibility of the fragility analysis will be improved. Finally, the form of knowledge tree technique (KTT) is proposed for treatment of epistemic uncertainties on fragility assessment.

I. 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 (ref. 1). 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 (ref. 2, 3) for seismic 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 the buildings and the equipments. 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

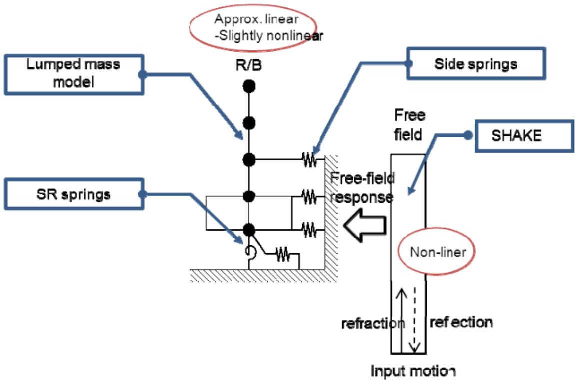


Fig. 1. Profile of Embedded Sway-Rocking Model.

consultation was developed for earthquake hazard assessment, this is the first time they were applied to fragility evaluation in Japan (ref. 4, 5, 6). 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 (Embedded Sway-Rocking (SR) model (SR model)) and a three dimensional (3D) 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 the soil to evaluate the fragility of the equipment. In this research, the uncertainty is evaluated as a dispersion against the SR model. Epistemic uncertainty relevant to fragility analysis is assessed by systematically eliciting knowledge of experts, in order to identify the sources and ranges of uncertainty. Through this assessment process, credibility of the fragility analysis will be improved. Finally, the form of knowledge tree technique (KTT) is proposed for treatment of epistemic uncertainties on fragility assessment.

II. EXPERT OPINION EXTRACTION

Our main target is earthquake response analysis using the SR model shown in Fig. 1, which is a standard model used in the fragility analysis of buildings and equipments. 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.

III. SENSITIVITY ANALISYS

III.A. Outline of Sensitivity Analysis for Expert-Opinion

We performed sensitivity analysis by using a constructed, embedded SR model and a 3D FE model to provide experts with results for expert-opinion elicitation. To validate the constructed analytical models, an eigenvalue analysis and comparison with observed earthquake data were performed. 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. Table I shows the uncertainty parameters used in the sensitivity analysis. The FE 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. In particular, parameters seven, eight are related in soil, and parameters four, five are related in building.

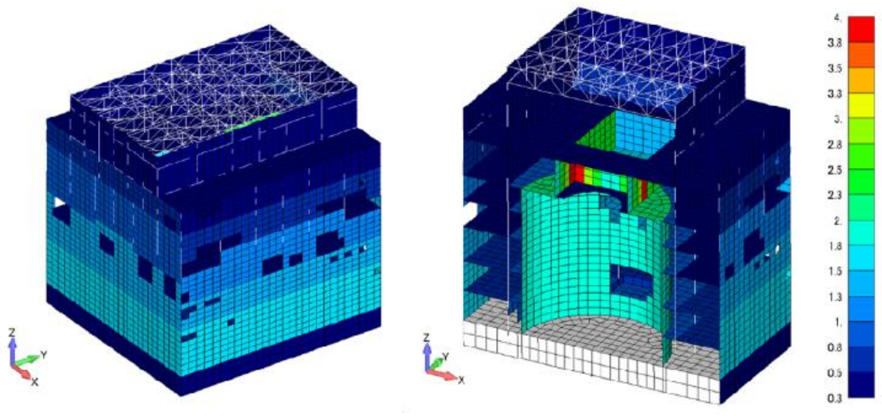
III.B. Summary of Reactor Building Modeling

The SR model and the 3D FE 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 3D FE 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 (ref. 7) and confirmed to be consistent with the results. In this section, we summarize the construction of the 3D FE model. We performed sensitivity analysis by using a constructed, embedded SR model and a 3D FE model to provide experts with results for expert-opinion elicitation.

As a first modeling step, the 3D shape model was created using 3D Computer Aided Design (CAD) software. We created the FE model based on 3D shape model. The FE 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 FE model, the volumes of the columns, beams, walls, and floors were calculated. We defined the mass density of each floor of the FE model such that the total mass of each floor matched that of the SR model. Fig. 2 shows the FE model of the reactor building.

TABLE I. Uncertainty Parameters Used in the Sensitivity Analysis

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



(a) Bird's-Eye View (b) Cross-Sectional View

Fig. 2. FE Model of Reactor Building (color ramp indicates thickness of each element in meters).

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 I. The properties of the Soil-structure Interaction (SSI) springs of the FE model were determined by referencing the SR model of the ref. 7. The springs were arranged in the FE model by distributing the springs of the SR model along the interacting surfaces of the wall and the base mat. The locations of the SSI spring are shown in Fig. 3. The input seismic waves for sensitivity analysis are shown in Fig. 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.

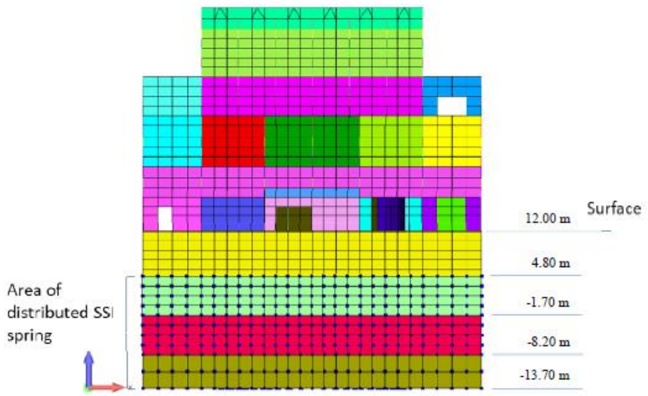


Fig. 3. Setting of SSI Springs.

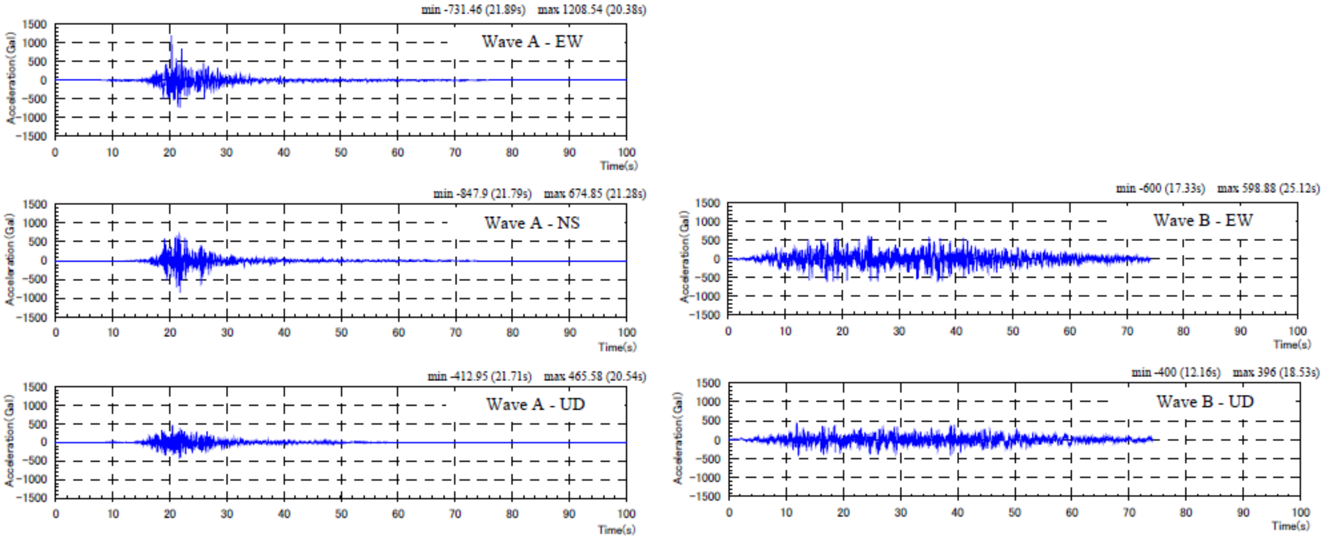
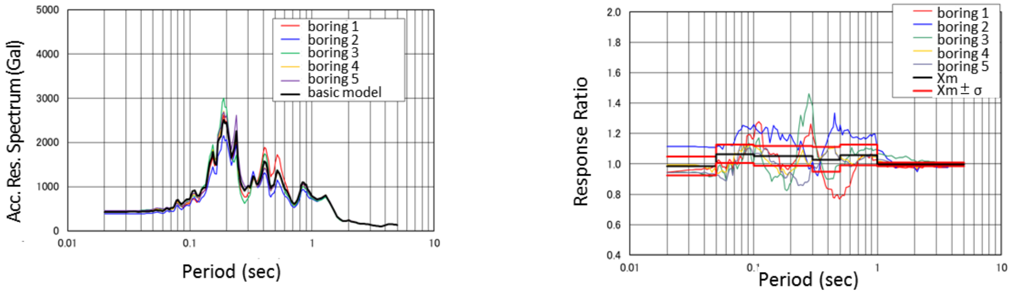


Fig. 4. Input Seismic Waves.

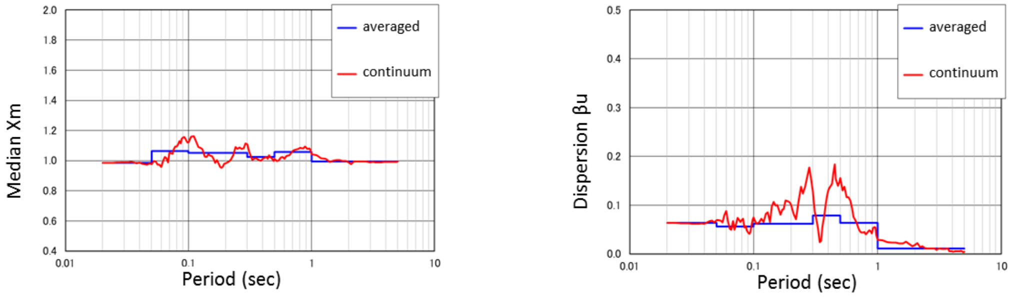
III.C. Result of Sensitivity Analysis

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. Fig. 5 shows an example of uncertainty evaluation for the material property of soil (Input wave A): (a) the acceleration response spectrum (h=3%) on the 3rd basement, (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, averaged dispersion values are lower than 0.1, dispersion values in continuum period range are almost lower than 0.1 and the maximum value is confirmed at specific period and the value is lower than 0.2. The uncertainty evaluations are also performed for backfill soil, boundary condition at base mat and side wall, and nonlinear effect of soil. Table III shows the uncertainty evaluation result on the 3rd basement for the soil properties. Fig. 6 shows the comparison of uncertainty evaluation result due to soil parameters. This result shows that the dispersion of material property of soil and backfill soil is remarkable as compared with boundary condition at base mat and side wall, and nonlinear effect of soil. The dispersion related to backfill soil parameters was particularly large in the 3rd basement, and the dispersion related to material property parameters of soil was overall large. On the other hand, the dispersion related to boundary condition at base mat and side wall was small in this condition. Fig. 7 shows the comparison of uncertainty evaluation results due to soil property, building property and SSI property. The dispersion value related to building parameters was larger as the floor level is higher. And it is found that the dispersion values related to soil and SSI parameters were dominant at the 1st and 3rd basement, where important equipment were set. It is also confirmed that the median value related to building parameters are lower than 1.0. It means that the results of SR model related to building parameters was larger than those results of FE model.



(a) Acceleration Response Spectrum

(b) Response Ratio



(c) Median of Response Ratio

(d) Dispersion of Response Ratio

Fig. 5. Uncertainty Evaluation with the Median and Dispersion for Material Property of Soil (Input wave A, B3F).

TABLE III. Uncertainty Evaluation for Four Kinds of Soil Parameter (Input wave A, B3F)

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	0.985	0.063	0.897	0.084	0.975	0.001	0.959	0.018
0.05-0.10	1.064	0.057	1.031	0.082	1.116	0.002	1.035	0.079
0.10-0.30	1.052	0.062	0.988	0.078	1.064	0.003	1.059	0.008
0.30-0.50	1.026	0.079	1.030	0.102	0.929	0.000	0.896	0.037
0.50-1.00	1.057	0.064	1.034	0.002	1.032	0.000	1.047	0.015
1.00-5.00	0.996	0.012	1.006	0.001	1.006	0.000	1.001	0.005

IV. ELICITATION OF EXPERTS' OPINION ON UNCERTAINTY

IV.A. Elicitation Procedures

In order to reduce epistemic uncertainty on SPRA, we have attempted to extract expert-opinions through questionnaire and group discussion. The elicitation procedure was implemented for selected technical topics; uncertainty on soil response and on modelling of SSI effect. Since technical areas for eliciting expert opinions are soil dynamics, SSI in the fragility assessment of structures, systems and components (SSCs), CE experts, who had ample knowledge and much experience in the respective field, and had some experience of plant design and analyses were selected. There are two expert groups formed in this project: six experts in the field of buildings and soil ground (CE experts) and eleven experts in the field of pipe and equipment (ME experts). Specifically, CE experts were asked regarding reactor building response and soil behavior under input ground motions (GMs), and ME experts were asked regarding equipment and piping behavior under the GMs. A questionnaire survey was conducted by starting to ask a series of questions to the CE experts were made regarding the basic knowledge on the target technical area, which included soil response analyses of SHAKE, SSI effect and the SR model in the first round of elicitation, and building responses, and modeling interface between structure and equipment in the second round. Elicited opinions were then disclosed to the other CE experts, and expert opinions were exchanged under the assistance of the technical integrator (TI). The elicitation includes opening workshop, questionnaire survey, and multiple workshops. All elicited opinions were carefully examined for development of the generic knowledge tree (GKT), which will be mentioned in the following chapter.

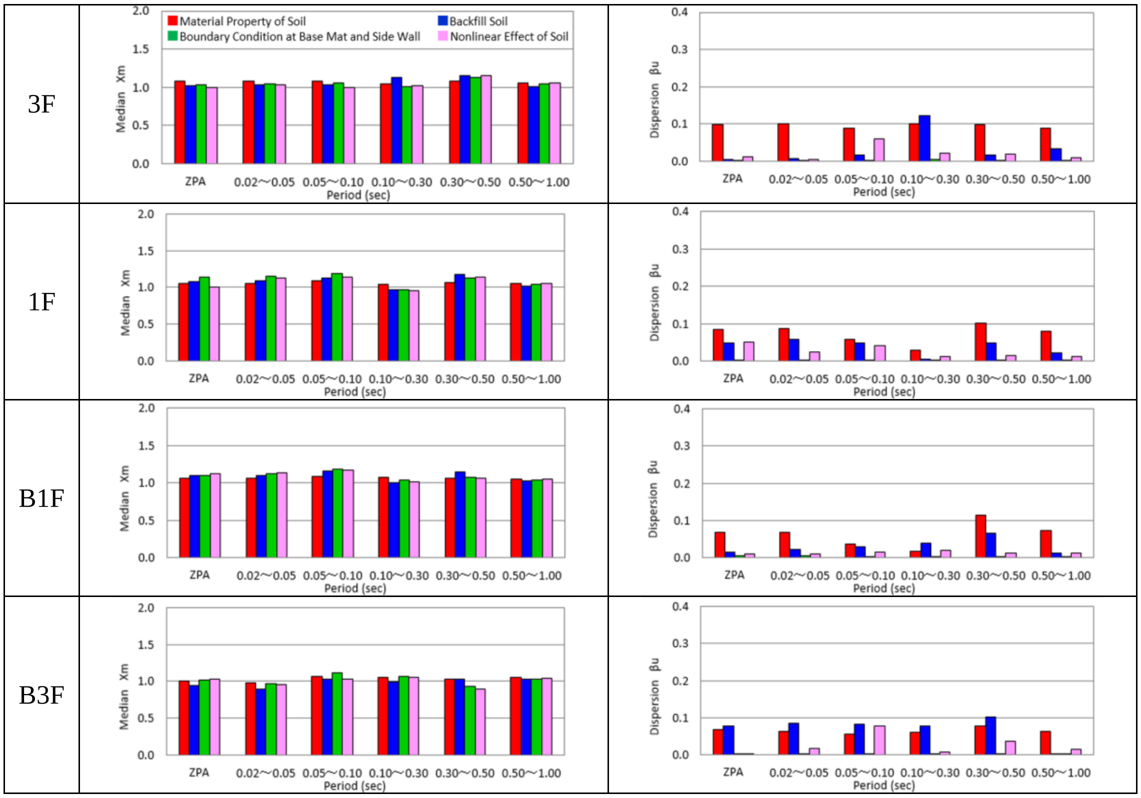


Fig. 6. Comparison of Uncertainty Evaluation Result due to Soil Parameters.

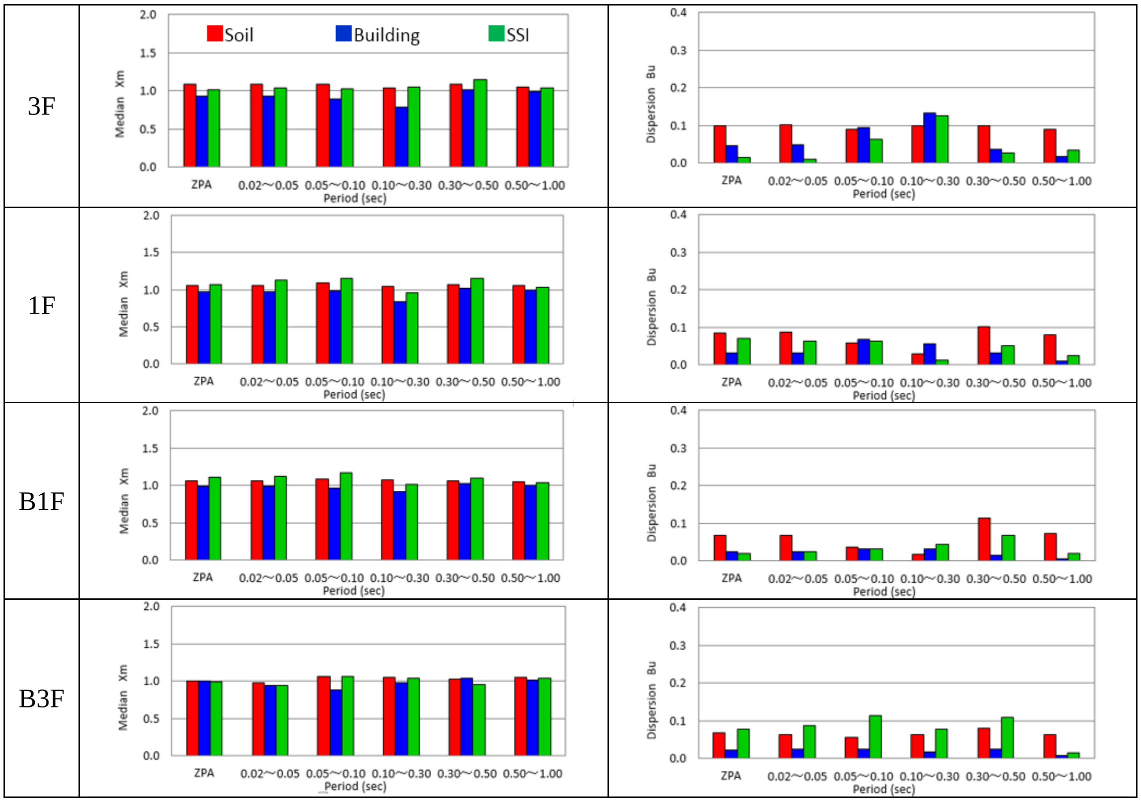


Fig. 7. Comparison of Uncertainty Evaluation Result on Soil and Building.

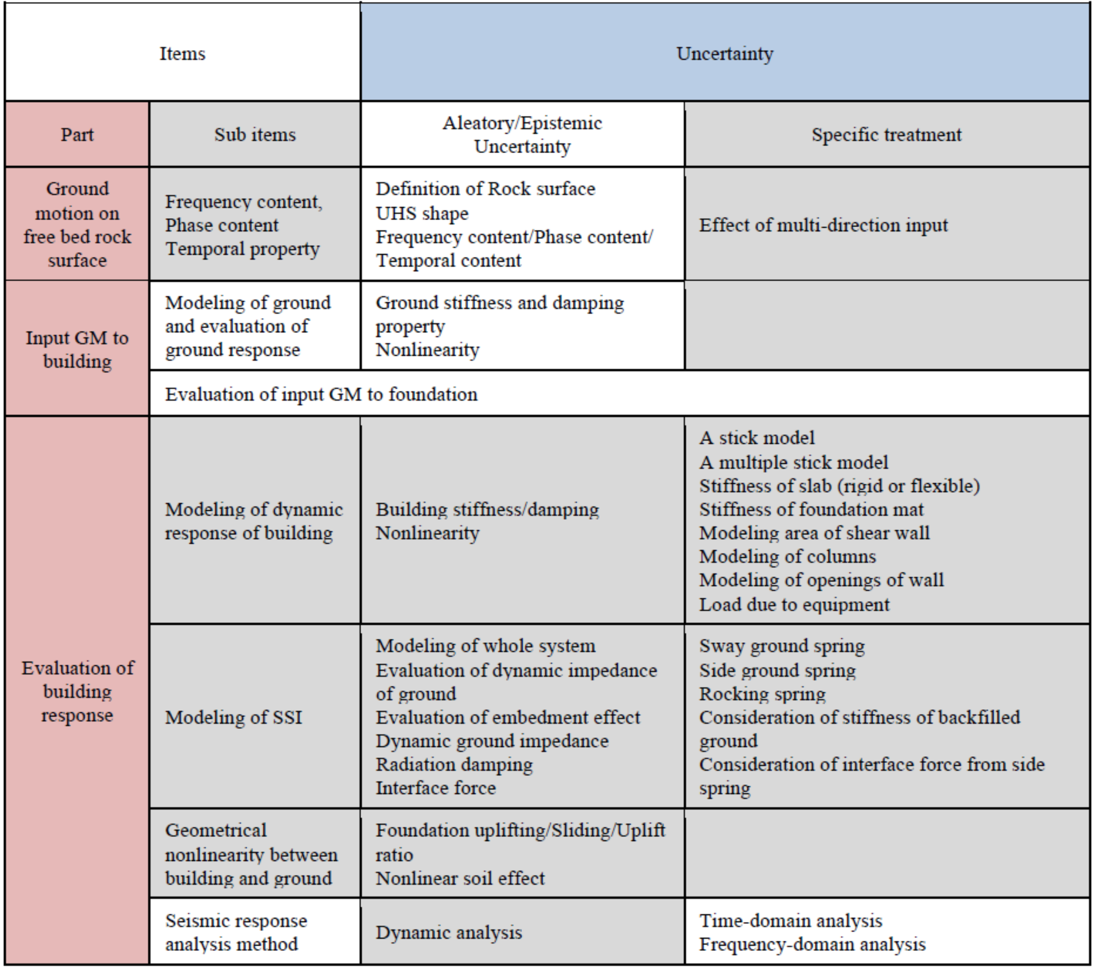
IV.B. Knowledge Tree Technique (KTT)

To evaluate epistemic uncertainty for the fragility assessment of an NPP, knowledge elicitation from experts in this project are categorized into the generic expert knowledge and the specific expert knowledge for further utilization of the knowledge data thus collected, as are seen in Table IV. Some opinions acquired from the elicitation processes are general, and possibly applicable to all NPPs, while other opinions are site-specific or reactor type-specific, and could be obtained from limited cased and from results of the sensitivity analyses of the specific NPP. Table V is the generic knowledge table related to aleatory or epistemic uncertainties which should be taken into consideration in the course of the fragility assessment of SSCs. If some of treatments are considered to give critical effect on the fragility assessment, the sensitivity analysis should be performed to quantify the influence. Then, a set of the generic knowledge trees (GKTs), a part of which is shown in Fig. 8, are prepared as common basis on which various uncertainties can be identified and quantified in the fragility assessment. In the figure, the GKT can indicate visually several notes when modelling a building structure with some notes prepared by TI. When the site condition or reactor type are different, the site-specific knowledge tree (site-SKT) can be developed through easy modification of the GKT shown above.

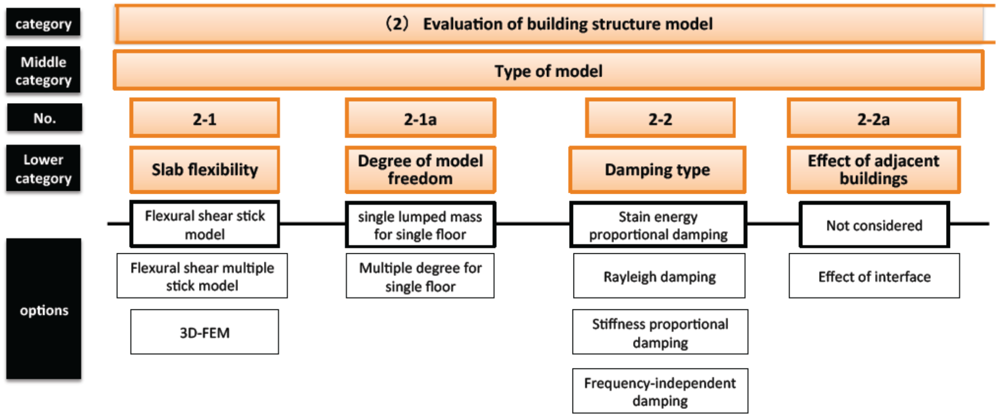
TABLE IV. Generic Knowledge and Specific Knowledge

Generic Expert Knowledge	General knowledge, findings and views regarding SSC seismic fragility evaluation
Specific Expert Knowledge	Specific knowledge dependent on site location, site conditions, reactor type, design conditions, etc. This category of knowledge reflects multiple expert opinions, results from sensitivity analyses, and is based on modification of the generic expert knowledge

TABLE V. Generic Knowledge Table



Items		Uncertainty	
Part	Sub items	Aleatory/Epistemic Uncertainty	Specific treatment
Ground motion on free bed rock surface	Frequency content, Phase content Temporal property	Definition of Rock surface UHS shape Frequency content/Phase content/ Temporal content	Effect of multi-direction input
Input GM to building	Modeling of ground and evaluation of ground response	Ground stiffness and damping property Nonlinearity	
	Evaluation of input GM to foundation		
Evaluation of building response	Modeling of dynamic response of building	Building stiffness/damping Nonlinearity	A stick model A multiple stick model Stiffness of slab (rigid or flexible) Stiffness of foundation mat Modeling area of shear wall Modeling of columns Modeling of openings of wall Load due to equipment
	Modeling of SSI	Modeling of whole system Evaluation of dynamic impedance of ground Evaluation of embedment effect Dynamic ground impedance Radiation damping Interface force	Sway ground spring Side ground spring Rocking spring Consideration of stiffness of backfilled ground Consideration of interface force from side spring
	Geometrical nonlinearity between building and ground	Foundation uplifting/Sliding/Uplift ratio Nonlinear soil effect	
	Seismic response analysis method	Dynamic analysis	Time-domain analysis Frequency-domain analysis



Q.2-2 uncertainty	moderate	-	moderate	-
Q.2-3 sensitivity	-	-	-	-
Sensitivity analyses	-	-	done	-
Importance by TI judgment	moderate	-	minor	-

Fig. 8. Example of Generic Knowledge Tree (Evaluation of building model).

V. CONCLUSIONS

We have attempted to obtain opinions on high-impact factors from experts to reduce epistemic uncertainty on SPRA through the expert-opinion elicitation. Also, we were able to confirm the relevance of the extracted factors in the sensitivity analyses. The analytical result 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. Furthermore, the standard procedure to evaluate epistemic uncertainty in the seismic fragility assessment of NPPs has been developed using expert opinions. Finally, the form of knowledge tree technique (KTT) for future fragility estimation is proposed. Effectiveness and shortcomings of the proposed method should be verified through further applications to real NPP structures to improve the method.

ACKNOWLEDGMENTS

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