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ESTABLISHING KNOWLEDGE BASE FOR FRAGILITY ASSESSMENT OF NPP USING EXPERT OPINIONS

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Abstract

The assessment of seismic safety of nuclear power plant facilities has been performed by identifying and quantifying uncertainties in seismic probabilistic risk assessment (SPRA). The level 1 PRA consists of three steps to assess an annual core damage frequency (CDF); seismic hazard evaluation, fragility evaluation of buildings and equipment, and system analyses. For the evaluation process, all uncertainties are classified into either aleatory or epistemic uncertainty for their practical treatment for better understanding and quantification of them. Upon these evaluation, the uncertainties are generally quantified based on statistical data, uncertainty analyses, engineering judgment and experience. The past PRAs for NPPs show that there are much more uncertainty for risk assessment against external events. Especially the epistemic uncertainty in the seismic PRA is difficult to quantify, and it often and perhaps only relies on expert judgment in earthquake engineering.

Therefore, in this study, systematic evaluation of the epistemic uncertainty on the seismic fragility of structures and equipment is studied and implemented for a model NPP in Japan. There are two expert groups formed in this project: experts in the field of buildings and soil ground (CE experts) and experts in the field of pipe and equipment (ME experts). Each group conducted a pilot study on the use of expert opinion elicitation assisted by technical integrators for uncertainty evaluation in fragility analyses. Along with ample results from relevant sensitivity analyses conducted, elicited opinions are carefully treated and classified into several specific areas and integrated into the form of knowledge tree (KT), all of which can be utilized for improving fragility estimation. In the three-year project, the standard procedure to evaluate epistemic uncertainty in the seismic fragility assessment of NPPs has been developed using experts judgements. For formal elicitation procedures, the SSHAC(Senior Seismic Hazard Analysis Comittee) procedure is well known and has been often used in the probabilistic seismic hazard analyses. However, no similar study has been reported for the fragility assessment so far. Effectiveness and shortcomings of the proposed method should be verified through further applications to real NPP structures to improve the method.

Keywords: Seismic safety, uncertainty, expert knowledge, response analysis, opinion elicitation

1. Introduction

Risk concept has drawn a great attention in Japan after the Fukushima Daiichi accident [1]. It is quite natural owing to the fact that we had a severe accident in Fukushima Daiichi NPPs due to unexpected tsunami wave and earthquake, and these should be essential need of in-depth consideration of countermeasures against such events beyond design basis. Importance of Probabilistic Risk Assessment (PRA) against external events has been highly recognized recently in Japan [2] and a new risk research center has been founded to promote PRA in electric power Japanese industry [3], where Dr. Apostolakis, a former commissioner of USNRC, is the head of the new center and has been promoting risk-informed decision making (RIDM) in all over Japan.

In 2006, a seismic design guideline for NPPs has been revised [4], indeed, 25 years after the last major revision was made in 1981. All revised key issues are obviously related to uncertainties lying in the whole design process to ensure seismic safety against future earthquakes. Especially, design basis ground motions have been revised drastically. A single level of design basis ground motion has been adopted and is based on maximum credible earthquakes which are deterministically estimated on the basis of seismological findings and evidence taking careful consideration of various inherent uncertainties. Advanced methodologies have been adopted to reduce uncertainty including improvement of accuracy, and to partially adopt probabilistic approaches to evaluate “residual risk” and to keep the risk as low as possible since it is understood that uncertainty cannot be fully eliminated.

In 2007, the Niigata-ken Chuetsu-oki earthquake struck the Kashiwazaki-Kariwa NPPs. The plants were safely shutdown with minor damage even on non-critical facilities and components. It should be noted that the records observed on the base-mat of the reactor buildings exceeded the design level by twice and more, but the plants showed excellent performance under the unexpectedly large seismic shaking. It is attributable to the potential seismic margin of structures and components, some of which are considered to be intentionally or non-intentionally taken in a design as well as in construction processes. It was surprising that SSCs had much more margin than originally expected in the design stage. It leads to emergent need to assess how safe structures, systems and components (SSCs), in reality, are against future earthquakes [5].

In 2006, just before the Kashiwazaki event, AESJ standard of seismic PRA was issued first in Japan [7] and has been revised recently in 2015, and their English translations are now available from AESJ. This came, indeed, 17 years after implementation of PRA for external events in the US, which is known as IPEEE (Individual Plant Examination for External Events [6]). Then the Fukushima Daiichi accidents has brought important lessons that there should be underlying unknown uncertainties, some of which have been implicitly or explicitly taken into consideration so far. It was a great surprise for everyone that the reactor could easily reach its critical state and collapsed with accompanying by great consequence. In addition to them, there still remains unknown uncertainty, which can be treated only by defense-in-depth concept in the framework of broader risk management [8]. It needs further discussions on how to treat and how to be well prepared for the unknown uncertainties.

The former US PRA showed typical results of PRAs for different hazards, as in shown in Fig.1, where risks due to external events, seismic risk in particular does reveal larger uncertainty, compared with those from internal events. It implies that there are lack of data, poor experience, limited knowledge, infeasibility of real-size experiments, etc., all of which suggest not only to consider epistemic uncertainties properly but to implement probabilistic risk assessment. Large uncertainties always tend to force us to set conservative safety regulation conditions which are often unreasonably stringent. Recognizing that there is much epistemic uncertainty in hazard assessment and in fragility assessment etc., plant safety has to be kept at the level of worldly recognized goal.

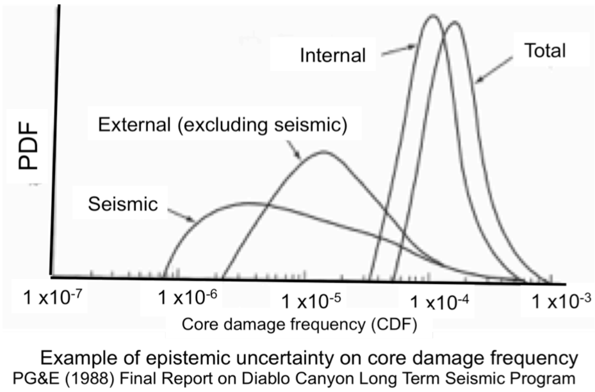

Figure 1 Example of epistemic uncertainty

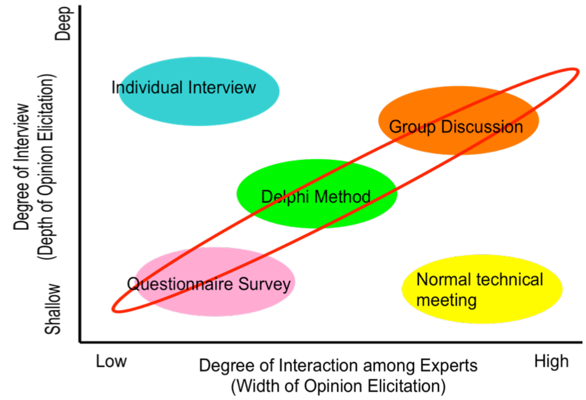

Figure 2 Typical ways of Opinion Elicitation

Therefore, for the safety assessment of NPPs subjected to large uncertainty, only experts judgement in various disciplines can play essential roles. Better understanding underlying uncertainties should rely on various ranges of expert judgments in different disciplines. To do so, several procedures for systematic treatment of experts judgement in probabilistic seismic hazard assessment (PSHA), in particular, were discussed intensively in the US in the late 1980s since the PSHA results from different organizations had significant disagreement [9]. Among them, in 1995, the standard, systematic and effective procedure to use experts had been discussed and proposed, which is renown as a SSHAC approach [10,11] and has been implemented several times widely in seismic hazard assessment in actual NPP sites in the world [12]. Although this procedure has been originally developed for PSHA applications, it can be in principle applied to any types of problems which expert judgements greatly dominate. Unfortunately, there is very few work with this procedure conducted for fragility estimation in seismic PRA framework so far.

As observed from the past Japanese recent experiences; from Kashiwazaki-Kariwa in 2007 and from Fukushima Daiichi in 2011, it is no doubt needed that not only seismic fragility of the SSCs but that of the whole plant should be estimated as realistically as possible, despite presence of large uncertainty. This is the motivation of this study, and the SSHAC-like approach to use experts will be implemented to estimate seismic fragilities of SSCs. Uncertainties associated with seismic response analyses of SSCs will be discussed and finally quantified since among all uncertainties in the fragility assessment, epistemic and aleatory uncertainties associated with response estimation under the condition of specified PGA are quite large. Epistemic uncertainty relevant to fragility analysis is assessed by systematically eliciting knowledge from experts, in order to identify the sources and ranges of uncertainty. Through this assessment process, credibility of the fragility analysis will be improved. Finally, a guideline for treatment procedure of epistemic uncertainty is proposed in this study.

2. Elicitation Of Experts' Opinion On Uncertainty

2.1 Past Systematic Elicitation Procedures

Figure 2 shows typical elicitation procedures depicted in the two-axis domain; width (X-axis) and depth (Y-axis) of opinion elicitation. These procedures are those from normal questionnaire surveys, individual interviews, to interactive meetings. Effectiveness of each procedure depends on intended purpose of opinion elicitation. It is well known that it is not easy to adequately and effectively elicit opinions from multiple experts. Important key issues; independence, unbiasedness, scientific soundness, quality of evidence, etc., are important all of which should be taken into consideration in the elicitation process.

2.2 Adopted Procedure

The past experience of the authors show that the following procedures are found to be very effective and were used before [13].

1) A questionnaire survey to each expert is effective because most of experts, who are always busy, can use their spare time for answering and commenting on several questions given, and their opinions are usually provided in a written form (answer sheets), which can be kept as individual and independent records, with which they can demonstrate their opinions in the following interactive meetings with other experts to amend their bias and to avoid misunderstandings.
2) For vital, non-biased and effective discussion, workshops and technical meetings should be held and be assisted either by a technical integrator (TI) or by a technical facilitator (TF), which has been proposed in the SSHAC procedure with great success [10, 11].
3) Interactive discussion with other experts, guided by the TI, should be encouraged and is very effective to promote the synergy effect within the expert group.
4) Sensitivity analyses can help experts to understand complex phenomena and concentrate on more significant uncertainty.

Based on the above observations, the elicitation procedure had been fixed and was implemented for selected technical topics; uncertainty on soil response and on modelling of soil-structure-interaction (SSI) effect. The elicitation includes opening workshop, questionnaire survey, and multiple workshops that follow. The results of sensitivity analyses are provided elsewhere.

2.3 Selection of Experts

Since technical areas for eliciting expert opinions are soil dynamics and SSI in the fragility assessment of SSCs, CE experts who had ample knowledge and much experience in the respective field and had some experience of plant design and analysis 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). The first author of this paper became a TI for discussion meetings of CE experts, and the fourth author for discussion meetings of ME experts.

3. Target Plant

3.1 ABWR Plant

A target plant is an advanced boiling water reactor (ABWR) building, which is considered to be embedded in the ground, as shown in Fig. 3. Our main purpose is placed more on evaluation of epistemic uncertainty relevant to the earthquake response of the reactor building and SSCs using an embedded Sway-Rocking (SR) model, as is seen in Fig. 4, which has been often used as a standard model in the conventional fragility and design analysis of a building and equipment.

The embedded SR model is considered to properly represent the SSI effect including embedment effect on the SSCs response, and together the 1D-wave propagation model called "SHAKE" is used to evaluate the input ground motion to the SR model. Nonlinear behaviour of surface layers was taken into consideration by introducing iterative equivalent linear analyses. Time history nonlinear dynamic response analyses using the SR model have been conducted with selected GMs although a simple response evaluation method had been used as a practical method to estimate the SSC fragility curves.

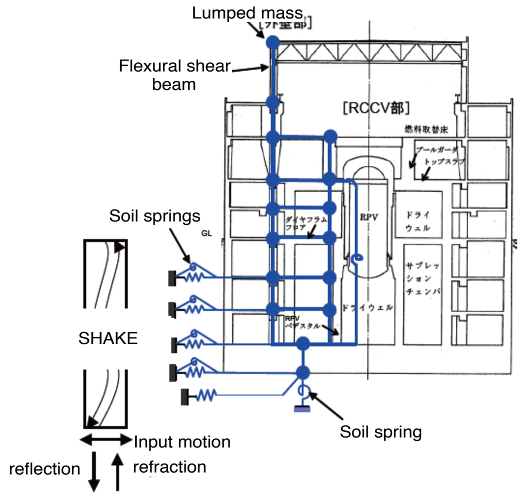

Figure 3 A model of reactor building

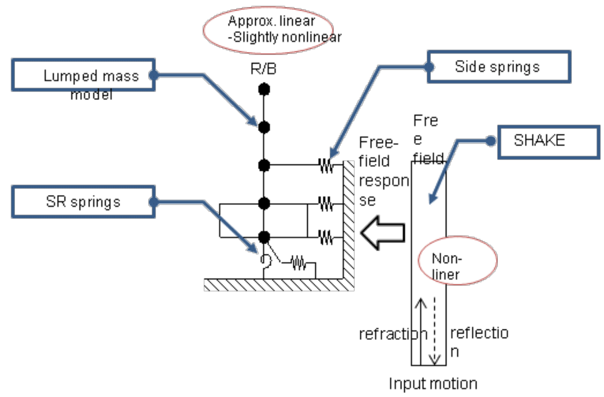

Figure 4 An embedded Sway-Rocking model

4. Implementation of Expert Opinion Elicitation

4.1 Opinion Elicitation Procedure

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, which 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 TI. The TI acted as a facilitator in the opinion exchange processes, allowing experts to give their opinions in a less constrained way so that subjects might be explored by in-depth discussion.

4.2 Basic Conditions for Opinion Elicitation

All CE experts are not the experts of SPRA, but are structural engineers in seismic design of NPP, professors in SSI research, experts in numerical analyses, experts in soil dynamics. Therefore, before the questionnaire survey, the purpose of the SPRA, the role of SSC fragility assessment, fundamental difference from design procedure was explained clearly to all CE experts. It was very much emphasized here that the purpose of the fragility assessment is not that of design in the respects that the former assesses realistic capacity and response without any conservatisms, while the latter is based on a set of design criteria given in the relevant design codes or guidelines.

The targeted state of the reactor building and the ground are clearly stated at the beginning as follows,

1) GMs to be used in the fragility assessment is approximately as twice as the design basis ground motion (Ss), which is, of course, the beyond design basis event, approximately corresponding to the damage initiation level of equipment,
2) A building may exhibit slightly nonlinear response behavior,
3) Equipment may start to exhibit vibrational or functional damage,
4) Soil may become nonlinear due to the excessive input, dependent on soil profile.

The above were conditions given before implementing the questionnaire survey.

4.3 Results from Questionnaire Survey

When all experts were asked about degree of uncertainty in the estimation of structural and mechanical responses from the embedded SR model at the very beginning of the questionnaire survey, the CE experts showed their opinions as listed in Table 1. The question was made as "which parts, do you think, have largest uncertainty for response estimation?"

Table 1 Classification of epistemic uncertainties addressed by CE experts
(Parts with largest uncertainty)

	Input data collection	Estimation of sensitivity	Analytical method		Overall
			Modeling	Discretization	
Building		Local Vibration		A stick model	
SSI		Geometrical nonlinearity (sliding, uplifting, detachment) building-building interaction	Geometrical nonlinearity (sliding, uplifting, detachment) Effect of side soil springs		
Ground	Soil property Mechanical (dynamic) property	Non-homogeneity -non-layered, -backfilled ground, -Topographically irregular ground	Damping of ground Nonlinearity of ground Equivalent linearization method	Division into sub-layers in SHAKE model	
Foundation			Location of bed rock		
Others	Input motion			Frequency range of analysis	Correlation btw. uncertainties

Their opinions were concentrated on the treatment of SSI effect under high acceleration excitation conditions, the evaluation of phenomena such as uplift of the foundation, horizontal sliding of the building, and the treatment of modeling of the building. Next, the experts were asked about effective parameters that should be considered preferably to perform sensitivity analysis of the target model plant. As a result, the experts raised the following issues,

1) Variability of ground motion input to the SR model
2) Nonlinear interaction effects of backfilled soil
3) Accuracy of SHAKE analysis for large-strain region, and for the effects of soil layer stratification
4) Accuracy of the embedded SR model including the effects of side soil springs from the viewpoint of equipment response.

Degree of uncertainty obtained from the group of ME experts was categorized into the following three concerns: the analysis model, the mechanical structures, and the interactions between soil, buildings and equipment structures. These results are shown in Table 2. The uncertainties included in these categories will be intensively extracted from the ME expert opinions as important issues in equipment-fragility assessment.

Table 2: Example of opinions elicited from ME experts

Uncertainty in mechanical structures	Response reduction due to Non-linearity of supports Dynamic behavior in high acceleration range Variability of material property Actual test results Development method of fragility curves
Uncertainty in analytical model	Combination of the response of the coupling of the analysis model Difference of floor responses in difference location of the same floor due to slab flexibility Correlation of equipment responses on the same floor Power (energy) pathway Calculation results and actual response How the multi-input evaluation is affected by displacement input Attenuation evaluation that depends on response acceleration Response error in how to tighten bolts
Uncertainty in the interactions between soil, buildings, and mechanical structures	Input ground motion Physical constant of soil Phase characteristics Correlation coefficient at multi-axis input Three-dimensional coupling

For the capacity of the equipment, data of seismic resistant verification tests of the actual sized equipment conducted in Tadotsu Engineering Experiment Station would be planned to collect and considered. In particular, a piping system was selected as static equipment and a large vertical pump was selected as dynamic equipment. As for the functional limits of the load-bearing structures, i.e., the active component and the foundation bolts for joining the mechanical structures and the building structure, further analysis and evaluation will be carried out, in reference to the analysis methods in the current technical provisions [14].

4.4 TI-facilitated Discussion

Three expert meetings were held, the first one was planned for briefing before conducting the questionnaire survey, the second was used as a workshop where each expert represented his opinion with showing his answer sheets to other experts and discussed interactively with others under the assistance of the TI, and the last one was a lap-up workshop where additional discussions were made and confirmation by each expert on how the elicited opinions were categorized and organized was made. All elicited opinions were carefully examined for development of the generic knowledge tree (GKT), which will be new concept and be mentioned in the following chapter.

5. Proposed Procedure for Opinion Elicitation

To evaluate epistemic uncertainty for the fragility assessment of an NPP, knowledge elicitation from experts in this project is categorized into the generic knowledge and the specific knowledge for further utilization of the knowledge data thus collected, as are seen in Table 3. Some opinions acquired from the elicitation processes in the last three years are general, and possibly applicable to all Japanese NPPs, while other opinions are site-specific or reactor type-specific, and could be obtained from limited cases and from results of the sensitivity analyses of the specific NPPs. The sensitivity analyses always can give all experts useful insight to identify significant parameters and treatment.

Table 4 is the generic knowledge table related to aleatory or epistemic uncertainty which should be taken into consideration in the course of the fragility assessment of SSCs. If some of treatments are considered to give

Table 3 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.

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. 5, 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.

6. Conclusions

In the three-year project, the standard procedure to evaluate epistemic uncertainty in the seismic fragility assessment of NPPs has been developed using experts judgements. Focusing on modelling of SSI and soil ground in assessment of equipment fragility, formal elicitation of expert opinions was done. Elicited opinions are carefully treated and classified into several specific areas and integrated into the form of knowledge tree (KT), all of which can be utilized for improving fragility estimation. The proposed method still needs further improvement.

7. Acknowlegement

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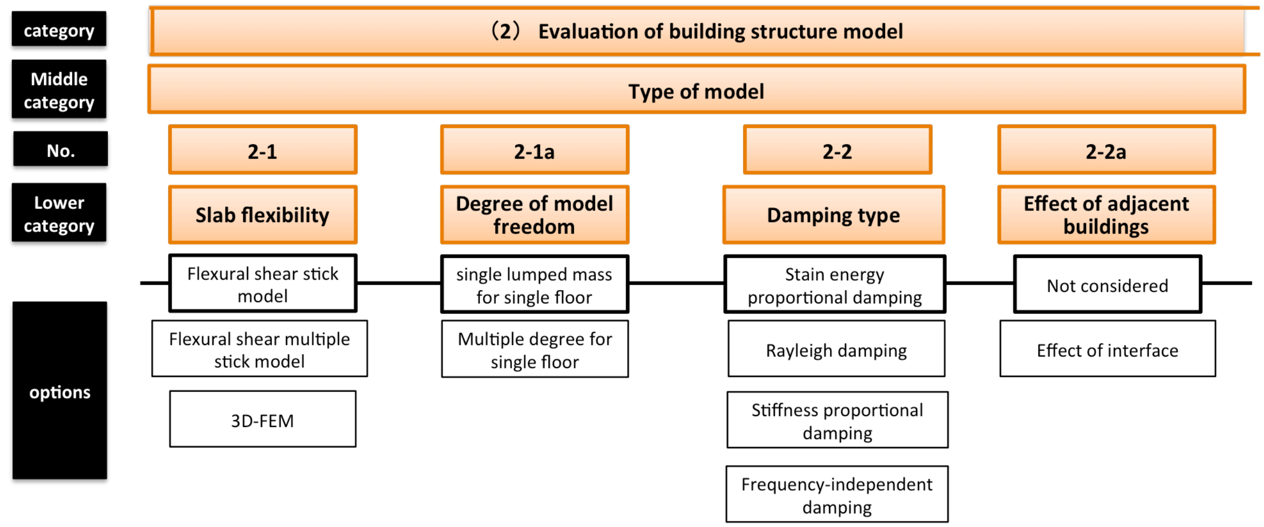
Table 4 Generic Knowledge Table

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	-

Figure 5 Example of Generic Knowledge Tree (Evaluation of building model)

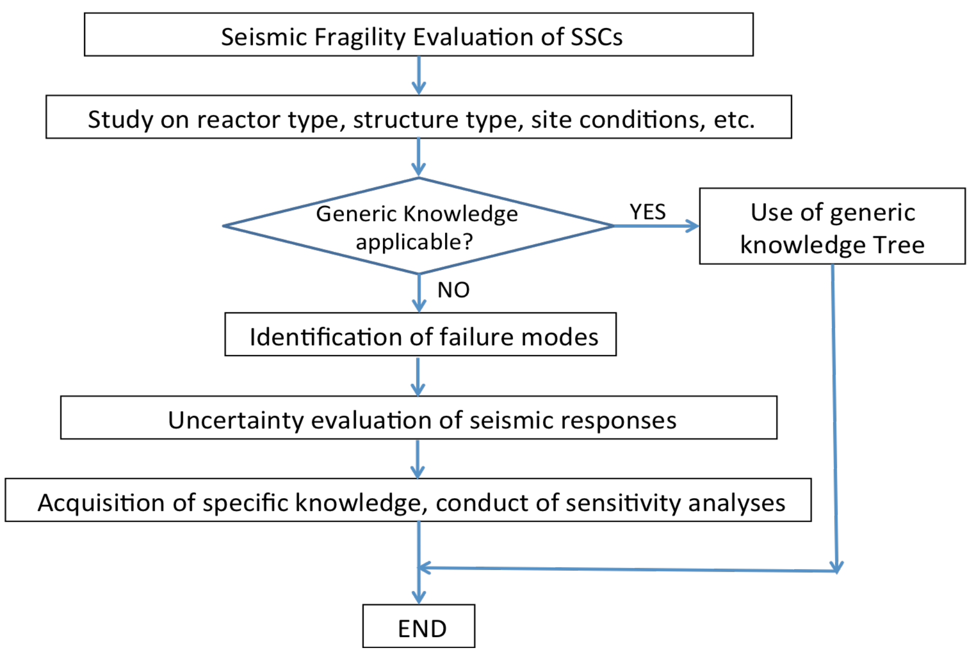


Figure 6 Flow of Uncertainty Evaluation