CURRENT STATUS AND IMPORTANT ISSUES ON SEISMIC HAZARD EVALUATION METHODOLOGY IN JAPAN

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The outlines of seismic PSA implementation standards and seismic hazard evaluation procedure were shown. An overview of the cause investigation of seismic motion amplification on the Niigata-ken Chuetsu-oki (NCO) earthquake was also shown. Then, the contents for improving the seismic hazard evaluation methodology based on the lessons learned from the NCO earthquake were described. (1) It is very important to recognize the effectiveness of a fault model on the detail seismic hazard evaluation for the near seismic source through the cause investigation of the NCO earthquake. (2) In order to perform and proceed with a seismic hazard evaluation, the Japan Nuclear Energy Safety Organization has proposed the framework of the open deliberation rule regarding the treatment of uncertainty which was made so as to be able to utilize a logic tree. (3) The b-value evaluation on the "Stress concentrating zone," which is a high seismic activity around the NCO hypocenter area, should be modified based on the Gutenberg-Richter equation.

KEYWORDS : Probabilistic Seismic Hazard Evaluation, Niigata-ken Chuetsu-oki Earthquake, Fault Model, Uncertainty, Logic Tree

1. INTRODUCTION

The Nuclear Safety Commission of Japan established a working group for examining "the regulatory guide for reviewing seismic design of nuclear power reactor facilities" in July 2001 so that the project to revise the regulatory guideline for seismic design could be started. After deliberating for almost 5 years, the new guideline was decided in September 2006 [1]. In the guidelines, the risk by the extension of the effect of the seismic ground motion that exceeds the design basis seismic ground motion Ss is defined as "the residual risk," and efforts to minimize "the residual risk" as low as practically achievable should be made. The commission also published the draft Interim report for safety goals in December 2003 [2] and the performance goal in May 2006 [3] as a part of the projects related to "residual risk."

Meanwhile, in September 2004, the Atomic Energy Society of Japan (AESJ) established 3 working groups (Seismic Hazard Evaluation, Building & Component Fragility Evaluation, and Accident Sequence Evaluation) to develop Seismic PSA implementation standards. The implementation standards were published in September 2007 [4].

The Niigata-ken Chuetsu-oki (NCO) earthquake occurred in the vicinity of the Kashiwazaki- Kariwa (KK) nuclear power plants on July 2007, and seismic ground motions that far exceeded those designed were observed at the KK plants. The NCO earthquake extremely affected the seismic safety of the KK plants. However, the functions of shutdown, cooling, and containment were maintained effectively. The Japan Nuclear Energy Safety Organization (JNES) carried out various cause investigations on the NCO earthquake and learned many lessons from it. As a part of the main lessons, JNES has been improving the methodology of the above-mentioned seismic hazard evaluation.

In this report, the outlines of the above seismic PSA implementation standards and seismic hazard evaluation procedure are shown. The overview of the cause investigation of seismic motion amplification on the NCO earthquake is also shown. Then, the improving contents of seismic hazard evaluation methodology based on the lessons learned from the NCO earthquake are described.

2. OUTLINES OF SEISMIC PSA IMPLEMENTATION STANDARDS AND SEISMIC HAZARD EVALUATION PROCEDURE

2.1 Seismic PSA Implementation Standards

The seismic PSA implementation standards consist of 8 chapters. Chapter 1 is the scope of application. Chapter 2 contains the definitions of technical terms. Chapter 3 of "Evaluation process" is dedicated to taking a general view of the composition of the current seismic PSA implementation standards as well as facilitating understanding the mutual correlation among chapters 4 to 8.

In chapter 4 of "Collection/Analysis of plant information and general analysis for accident scenarios," while collecting/analyzing information necessary for a seismic PSA and conducting a plant walk-down, a wide variety of earthquake-specific accident scenarios are defined, initiating events that trigger core damage accidents are analyzed, and a component list is formulated as a preparation of quantitative evaluation of core damage, which is the most serious type of accident in nuclear power plant accidents.

In chapter 5 of "Seismic Hazard Evaluation," by generating a model of location/size/occurrence frequency of earthquakes that may occur in the vicinity of the site in the future, the exceedance frequency of seismic ground motion caused by the earthquakes at each strength level is obtained.

In chapter 6 of "Building & Component Fragility Evaluation," by using their realistic response and capacity, the accumulated failure probability for each strength level of seismic ground motion is obtained.

In chapter 7 of "Accident Sequence Evaluation," accident scenarios that lead to core damage are analyzed, and, by using the seismic hazard evaluation result, fragility evaluation result, and plant system information, the occurrence frequency of a core damage accident sequence is obtained. In these evaluations, while reflecting domestic seismic design information, adequate considerations are given to uncertainty related to evaluation models and database.

In chapter 8 of "Documentation," the ground/judgment of adopting a specific model or data in the process of evaluation is stated. As a consequence, uncertain factors that seriously influence core damage, accident sequences, safety systems and components are identified and clearly described. From the standpoint of assuring clarity of explanation and transparency, these elements are summarized in the report.

2.2 Seismic Hazard Evaluation Procedure

The seismic hazard evaluation of chapter 5 is described in the following 7 sections as shown in Fig. 1.

(1) Collection of plant-related information

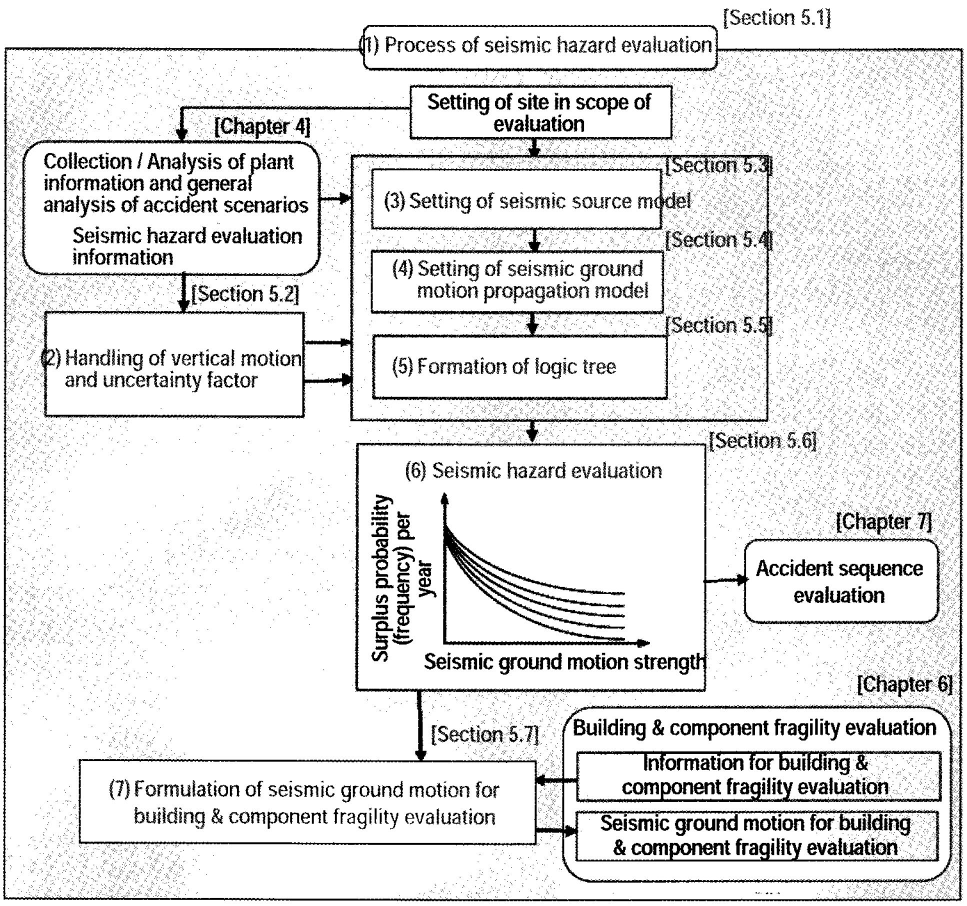

Fig. 1. Procedure of Seismic Hazard Evaluation [4]

(2) Treatment of uncertainty factor and vertical motion in the seismic hazard evaluation
(3) Setting of seismic source model
(4) Setting of seismic ground motion propagation model
(5) Formation of logic tree
(6) Evaluation of seismic hazard
(7) Formation of seismic ground motion for fragility evaluation

In the process of seismic hazard evaluation, modeling of location/size/incidence of earthquakes that may occur in the vicinity of the site is conducted using active fault data and historical earthquake data. The propagation of seismic ground motion caused by the earthquakes is evaluated based on a fault model or empirical attenuation model in order to obtain the relationship between the strength of seismic ground motion and the exceedance frequency/probability. The uncertainty in the modeling is treated by using a logic tree. The seismic ground motion for fragility evaluation is generated based on the seismic hazard evaluation result (target spectrum).

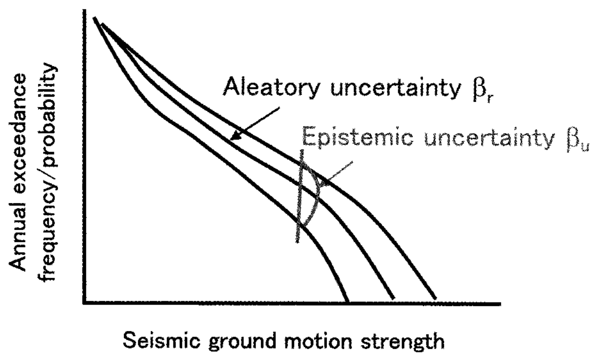

Fig. 2. Schematic Chart Regarding Treatment of Uncertainty on Seismic Hazard Evaluation

3. OUTLINE OF SEISMIC HAZARD EVALUATION PROCEDURE OF AESJ

3.1 Collection of Plant-related Information

The collection of plant-related information is an extremely important process that should be conducted in order to prevent omission of any site-specific condition as well as to enable effective implementation of the seismic hazard evaluation.

Examples of main earthquake-related data are as follows. Active fault data: New active fault in Japan sheet maps and inventories [5]. Historical earthquake data: Usami catalog [6], Utsu catalog [7], Japan meteorological agency catalog [8], and Seismo-tectonic structure zone maps (seismic activity and tectonic structure as shown in [9]).

3.2 Treatment of Uncertainty Factor and Vertical Motion in the Seismic Hazard Evaluation

3.2.1 Treatment of Uncertainty Factor

The uncertainty is categorized by two factors: aleatory uncertainty related to physical phenomena-specific randomness (βr) and epistemic uncertainty related to lack of knowledge or awareness (βu). The former is related to the dispersion characteristics that are intrinsic to the targeted phenomena. The level of dispersion cannot be reduced any more. The latter is related to the lack of knowledge or the uncertainty and difference in interpretation included in the modeling and evaluation process. It is expected that the uncertainty may be reduced in the future through an increase of knowledge or the development of science.

In seismic hazard evaluation, βr is considered in the seismic hazard curve as shown in Fig. 2, while the logic tree is used for *β*u, where it is considered an evaluation error of the hazard curve itself. As uncertainty factors are considered, factors that significantly affect the evaluation results shall be selected by using sensitivity analysis.

3.2.2 Treatment of Vertical Motion

In cases where there is a building/component with a significant impact of vertical motion in the building/component fragility evaluation, the seismic hazard of vertical motion shall be evaluated.

The source model with vertical motion shall be treated in the same way as with a horizontal motion. As a seismic ground motion propagation (SGMP) model, an available SGMP model within an empirical attenuation model or fault model for vertical motion shall be selected.

3.3 Setting of Seismic Source Model

The seismic source model is a probability model that represents the occurrence of earthquakes that may affect the concerned site in the future. The seismic sources are roughly divided into specific sources and region sources as shown in Fig. 3. Each type of source is defined by using parameters such as hypocenter location/geometry, magnitude of earthquake, and frequency (or probability) of earthquake occurrence based on active fault data and historical earthquake data. In order to evaluate frequency (or probability) of earthquake occurrence, either the Poisson process or the non-Poisson process (renewal process) shall be used.

The specific source model is the source model for which a hypocenter location and earthquake scale can be specified in advance. Unique earthquakes that occur at inland active faults or plate interfaces are considered as a scope. The region source model is the source model for a series of earthquakes that occur in a region with a certain width using the various historical catalogs in section 3.1. In this setting, aftershocks in these catalogs shall be excluded. A region shall be set up as a seismic source zone by considering seismo-tectonic structure as shown in Fig. 4 [9].

In setting the source model, aleatory uncertainty βr

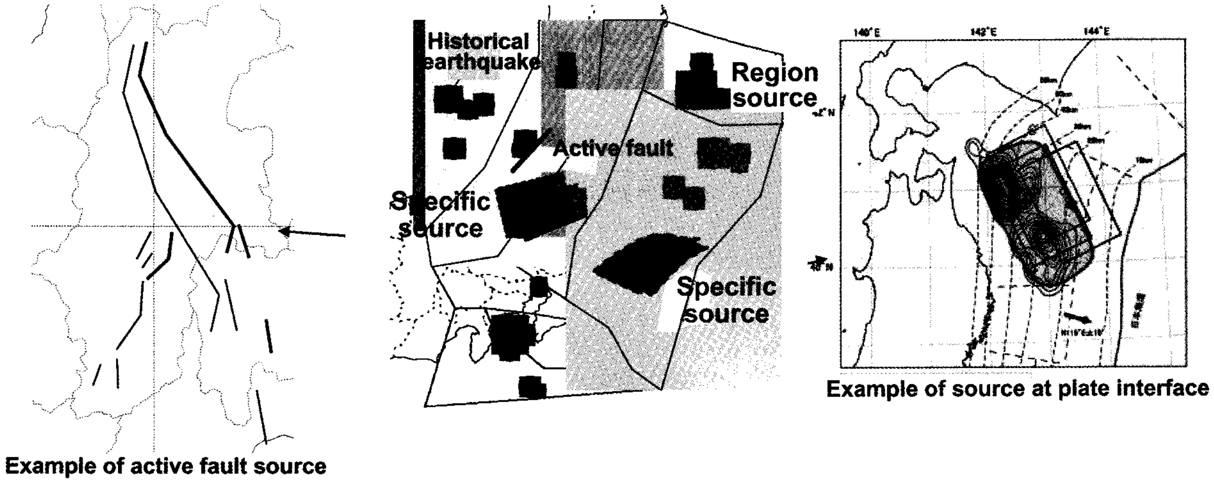

Fig. 3. Schematic Chart Regarding Setting of Specific and Region Sources

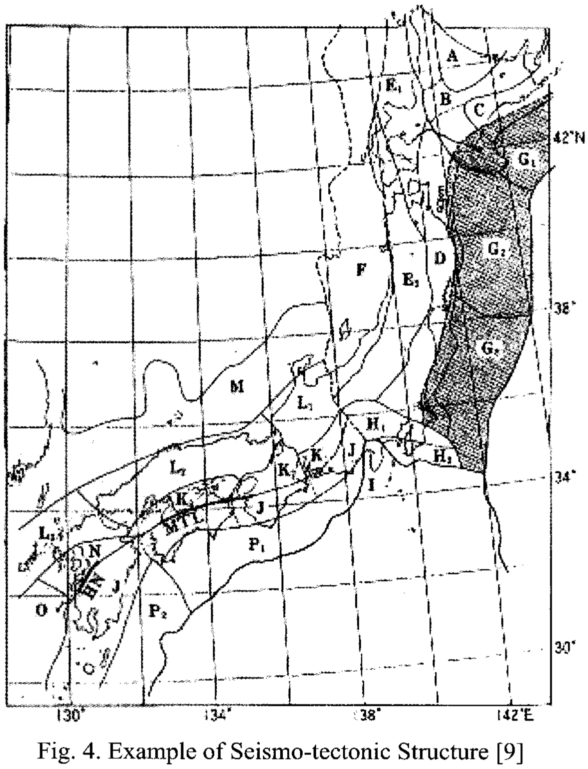

Fig. 4. Example of Seismo-tectonic Structure [9]

and epistemic uncertainty βu in subsection 3.2.1 shall be considered in an appropriate manner. The example of classification of uncertainty factors about the source model is shown in Table 1.

3.4 Setting of Seismic Ground Motion Propagation Model

When evaluating the seismic ground motion strength of the evaluation site, modeling of SGMP characteristics between the seismic source and the site is conducted. Depending on the volume of concerned information and advantage/disadvantage of each model, either the fault model or the empirical attenuation model as shown in Fig. 5 is selected. The SGMP model for horizontal seismic ground motion or vertical seismic ground motion in subsection 3.2.2 is selected.

Based on the defined SGMP model, the seismic ground motion strength at the concerned site is evaluated as a probability distribution. Logarithmic-standard deviation to represent dispersion and the upper limit value of seismic ground motion shall be set up. The upper limit value shall be set by considering the truncation.

In setting the SGMP model, aleatory uncertainty βr and epistemic uncertainty βu in subsection 3.2.1 shall be considered in an appropriate manner. The example of classification of uncertainty factors about the SGMP model is shown in Table 2.

3.5 Formation of Logic tree

The logic tree is formulated for the epistemic uncertainty factors selected in the setting of specific and region source models in Table 1 and the SGMP model in Table 2. Fig. 6 shows the example of a logic tree for the uncertainty of a fault model in Table 2.

The definition of technical difficulty and utilization level of expert opinion in the formation of a logic tree is as follows. Technical Integrator (TI) or Technical Facilitator/Integrator (TFI) shall be selected and the formulation procedure at each expert utilization level shall be followed in the formation of a logic tree. TI is a technical manager in the formation of a logic tree. TFI is a technical manager in the formation of a logic tree and coordinator of consolidating expert opinions.

In the formulation of a logic tree, technical difficulty

Table 1. Classification of Uncertainty Factors Regarding Source Model [4]

Items for which uncertainty is considered		Treatment in evaluation: Item considered as aleatory uncertainty βr	Treatment in evaluation: Item considered as epistemic uncertainty βu (evaluation by logic tree)
Specific source	Location·Geometry	· Change of fault location within the source area	· Setting of fault location · Necessary / Not necessary to consider segmentation
	Earthquake scale	· Change of earthquake scale	· Selection of earthquake scale evaluation formula
	Earthquake occurrence frequency	–	· Selection of earthquake occurrence frequency evaluation method · Setting of earthquake occurrence chronological model
Region source	Location·Geometry	· Based on the assumption that earthquakes occur uniformly within the source area (distance probability distribution)	· Selection of segmentation model
	Earthquake scale	· Magnitude probability distribution in b-value model	· Selection of b-value model (including data base) · Setting of maximum magnitude
	Earthquake occurrence frequency	–	· Selection of b-value model (including data base)

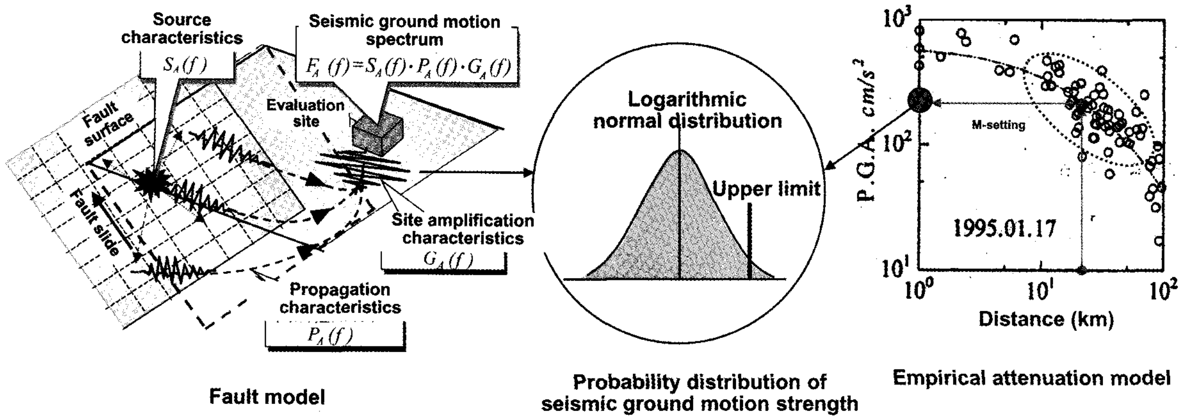

Fig. 5. Schematic Chart Regarding Setting of Fault Model and Empirical Attenuation Model

in the epistemic uncertainty factors to be considered shall be judged and any of the following 3 expert utilization levels shall be selected.

- **Level 1:** If the impact of uncertainty on the seismic hazard is relatively small, TI shall evaluate the community distribution based on the information and experiences that are collected/analyzed by himself to formulate a logic tree.
- **Level 2:** If the impact of uncertainty on seismic hazard is relatively large, expert opinions on important issues are expected to be split. In such a case, TI shall try to improve and screen the model by hearing expert opinions/joint discussion by model proponents and other concerned experts in order to evaluate the community distribution and to formulate a logic tree.
- **Level 3:** If uncertainty factors of seismic hazard are judged diverse, important, and complicated, TFI shall organize an expert panel. In such a case, experts shall be utilized as an objective evaluator instead of model proponents so that the community distribution evaluated by the panel can be consolidated in a fair manner to formulate a logic tree.

3.6 Evaluation of Seismic Hazard

The seismic hazard at a site shall be evaluated using the setting conditions based on the various procedures in

Table 2. Classification of Uncertainty Factors Regarding Seismic Ground Motion Propagation Model [4]

Items for which uncertainty is considered	Treatment in evaluation	
	Item considered as aleatory uncertainty βr	Item considered as epistemic uncertainty βu (evaluation by logic tree)
Empirical attenuation model (including site correction)	· Dispersion of empirical attenuation model (physical randomness included in the seismic ground motion) · Dispersion value, upper limit value	· Type of empirical attenuation model to be used (including error in modeling as funtions of earthquake magnitude and distance) · Dispersion value, upper limit value
Fault model	· In evaluating seismic ground motion by fault model, the randomness uncertainty included in the seismic ground motion (βr) and the epistemic uncertainty in modeling based on each type of fault parameters (βu) are mixed together. · If βr-related fault parameters can be isolated from other fault parameters, it is possible to evaluate βr of seismic ground motion strength also by using logic tree.	

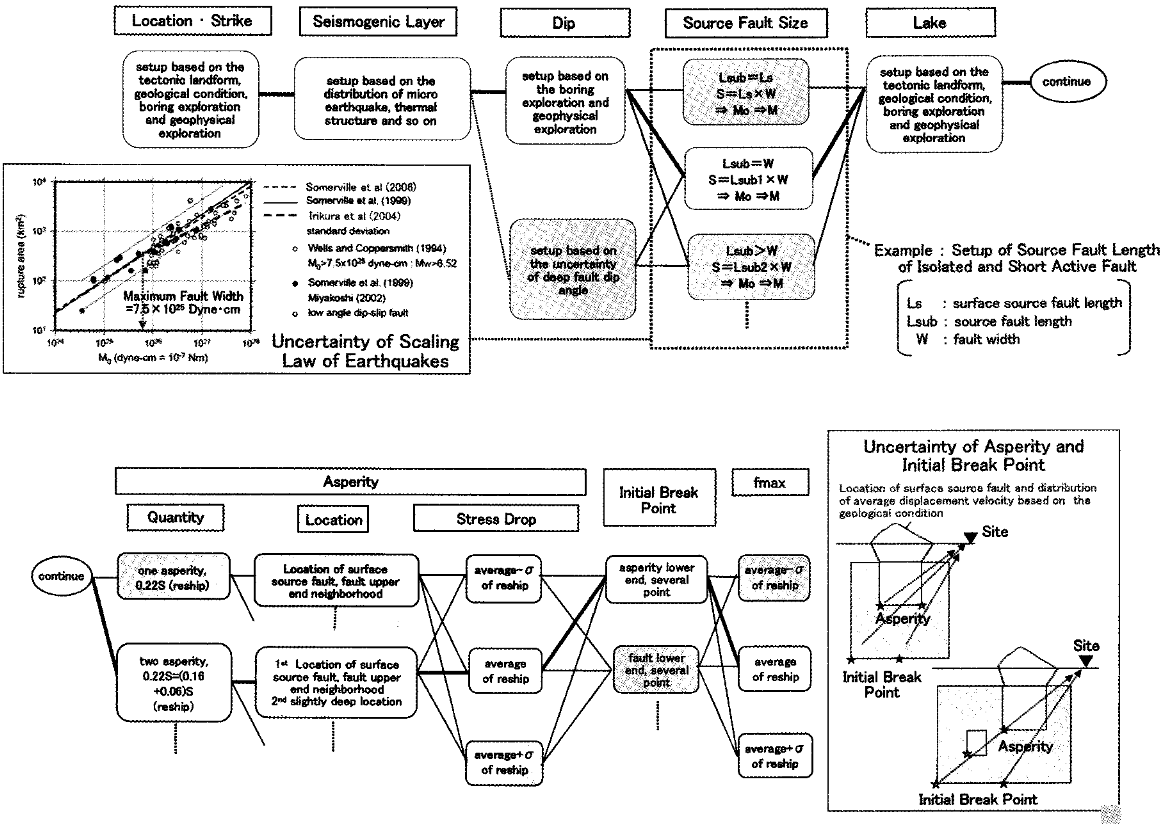

Fig. 6. Example of Logic Tree Regarding Fault Model

sections 3.1-3.5. Fig. 7 shows the example of a seismic hazard evaluation based on the fault model.

3.7 Formation of Seismic Ground Motion for Fragility Evaluation

In formulating seismic ground motion for a fragility evaluation, a setting method for period characteristics, chronological characteristics, and phase characteristics as well as the adjustment method to the period characteristics (target spectrum) is defined.

As a setting method of period characteristics, the appropriate method is selected based on the volume of

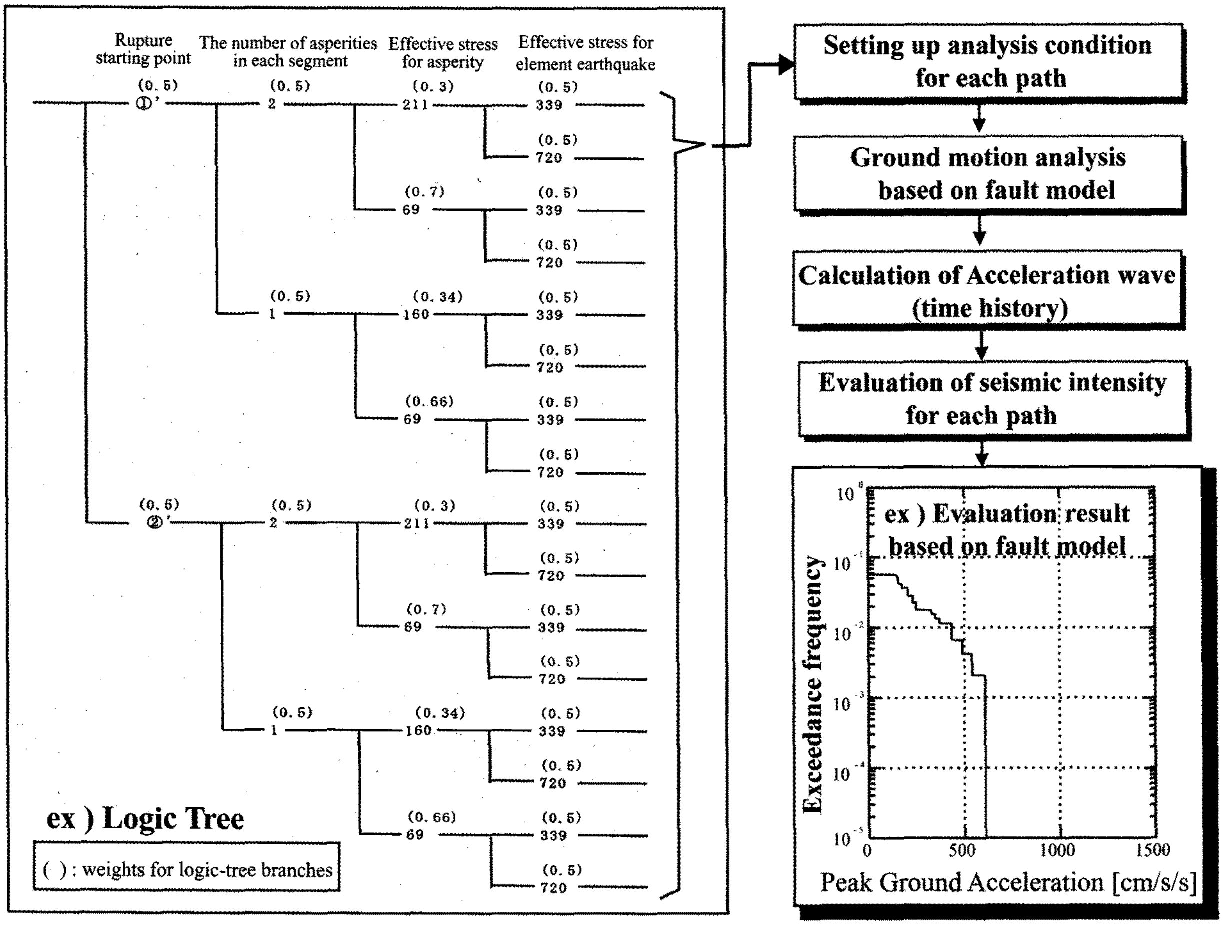

Fig. 7. Example of Seismic Hazard Evaluation Based on Logic Tree of Fault Model

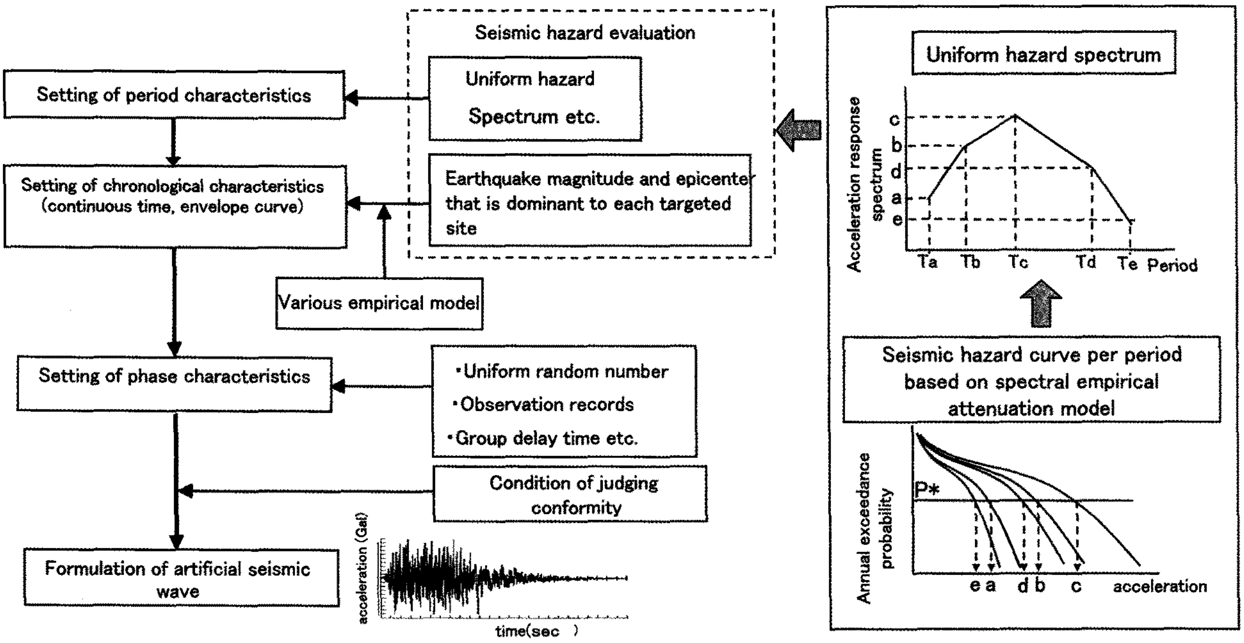

Fig. 8. Formulation of Seismic Ground Motion for Fragility Evaluation

related information and reliability level from those including the uniform hazard spectrum method, a method based on the evaluation of magnitude/hypocenter of the estimated earthquake through decomposition of seismic hazard as shown in Fig. 8.

4. IMPROVEMENTS OF EVALUATION METHODOLOGY BASED ON LESSONS LEARNED FROM NCO EARTHQUAKE

4.1 Usefulness of fault Model on Cause Investigation of NCO Earthquake

The seismic ground motions observed by the Tokyo Electric Power Co. that occurred during the NCO earthquake at the KK plant are shown in Fig. 9. The following cause investigation was required [10].

(1) Why did 3 pulses happen?
(2) Why did the observed seismic ground motions exceed those designed and Unit 1 show the highest values which are nearly double the design response?

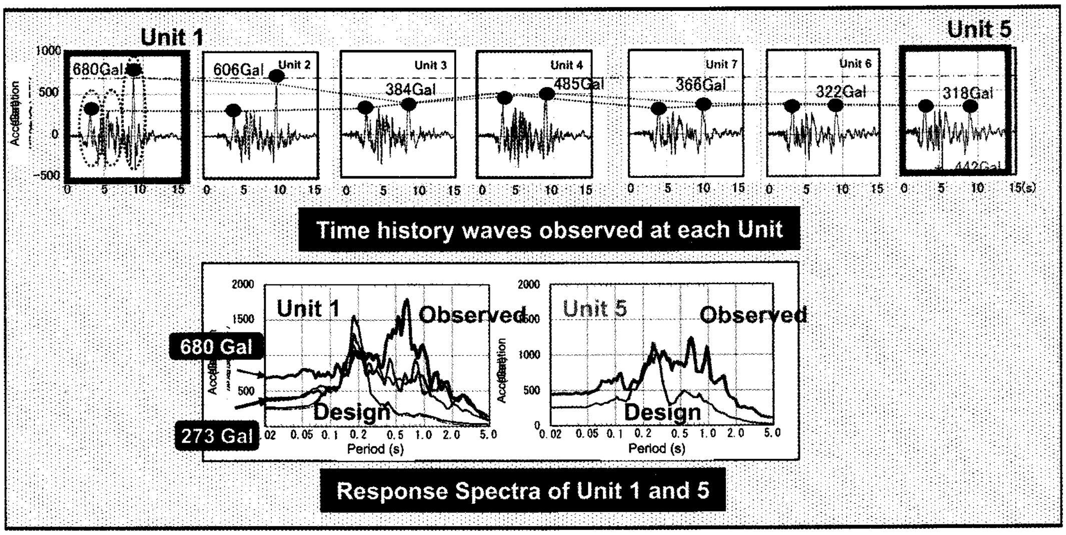

Fig. 9. Time History Waves Observed at Niigata-ken Chuetsu-oki Earthquake and their Designed and Observed Response Spectra

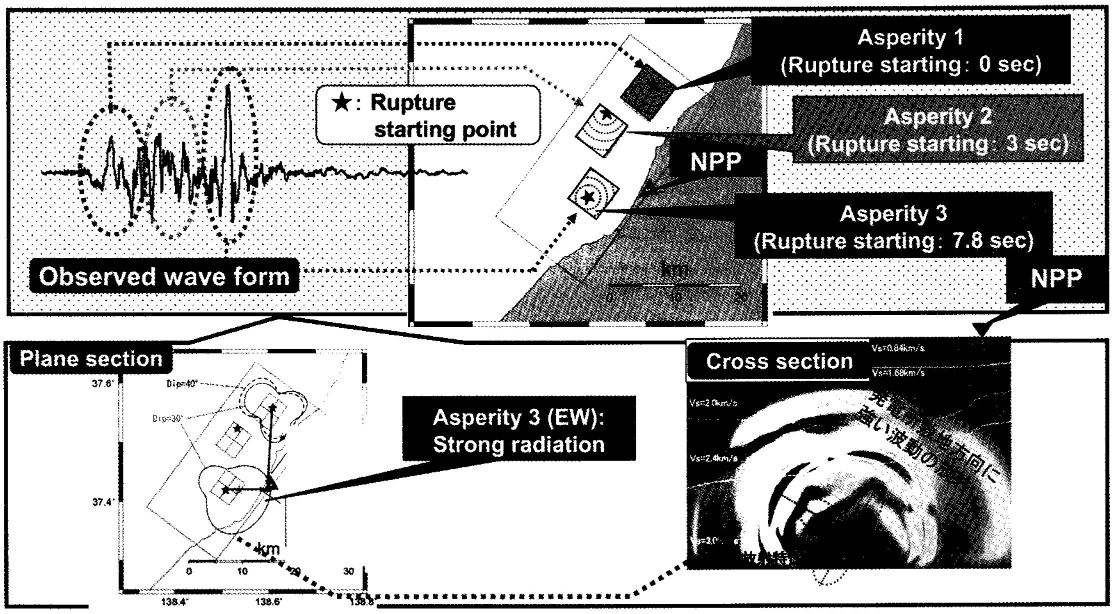

Fig. 10. Schematic Chart Regarding Relationship between each Pulse Wave and Asperity and Strong Radiation Characteristic at Asperity 3 Obtained from Simulation Analyses by Fault Model

This cause investigation was conducted using a fault model and its validity was through the cause investigation.

4.1.1 Analysis of Effects of Source Characteristics

The analysis of the effects of source characteristics was carried out by simulation analysis by using the fault model as shown in Fig. 10. The results of the cause investigation were as follows [10]. Sequential rupture of 3 asperities which broke out a strong seismic motion was one of the causes of the amplifying pulse wave. Asperity 3 was very close to the site, and radiated a strong seismic motion.

4.1.2 Analysis of Amplification Characteristics of Pulse Waves at Unit 1

In order to clarify the effects of deep ground structure, JNES generated a 3-D underground structure model using boring surveys, reflection surveys, geological maps, etc., performed by the former Japan National Oil Corporation. The main characteristics of the 3-D underground structure model are as follows [10]. Earthquake bedrock near the site was as deep as about 5~8 km. The deep underground structure had irregularity in its propagation path of seismic motion from the epicenter.

The analysis of amplification characteristics of pulse waves at Unit 1 was carried out using the 3-D underground structure model and the simulation waves by the fault model as shown in Fig. 11. The results of the cause investigation were as follows [10]. Irregularity in the deep underground structure concentrated and stored seismic ground motion energy, and tended to lead seismic motion to the site. The pulse wave at the layer near free bedrock was amplified largely. The amplifying factor was 3~4 times.

4.2 Utilization of Fault Model for Sources Near the Site

The cause investigation on the amplification factor of seismic ground motion on the NCO earthquake was achieved by using a fault model and 3-D underground structure model. In other words, the cause investigation would have been difficult if the fault model was not available. In many cases, seismic hazard of a nuclear site is generally dominated by near sources inside about a 60 km radius. Therefore, detail evaluation for near sources is essential. The setting of the SGMP model in section 3.4 describes the selection of either the fault model or the empirical attenuation model. In addition, it is also very important to recognize the effectiveness of the fault model in the viewpoint of the detail evaluation of seismic source and ground motion and the resolution on their mechanisms. Then it is also important to outgrow from evaluation by the empirical attenuation model only.

The detail evaluation is achieved by the fault model method with the setting of 16 parameters as shown in Fig. 6. However, at a site where less information is available on these parameters, caution should be paid to the large uncertainty. Hereafter, it is very important to improve the fault model method from the viewpoint of the quantitative

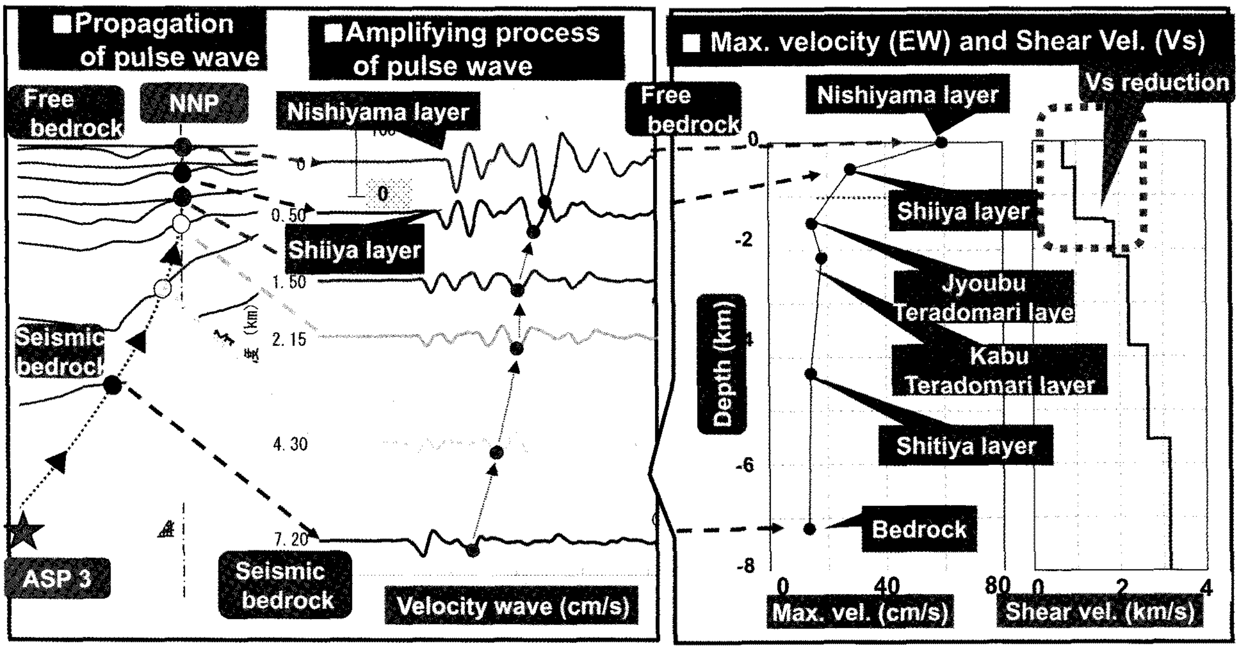

Fig. 11. Schematic Chart Regarding Time History Waves and Maximum Velocities at each Layer of Deep Ground Structure by Propagation Analyses and their Shear Velocities

evaluation on the uncertainty of each parameter and interaction between parameters.

4.3 Improvement of Treatment of Uncertainty in Source and Seismic Ground Motion

The new seismic design review guide requires consideration of uncertainty concerned with the evaluation process of the design basis ground motion Ss and also refers to its exceedance probability. The latest findings from the NCO earthquake also show the necessity for the consideration of uncertainty. In the open committees of the regulatory body, deliberation on the exceedance probability of Ss based on the probabilistic seismic hazard evaluation is being conducted, but it is not proceeding efficiently. Its reasons are as follows: there are few committees knowing probabilistic seismic hazard evaluation well enough and there is no rule for its deliberation.

There are many opinions from regulatory bodies and utilities that seismic hazard evaluation for each site should be performed along the open deliberation rule by a public organization such as JNES. JNES has proposed a framework of the open deliberation rule as shown in Table 3, which was made so as to be able to utilize the logic tree practically, referring to the formation of a logic tree in section 3.5.

4.4 Improvement of b-value Evaluation Method in Stress Concentrating Zone

The seismic activity around the NCO hypocenter area is much higher and is a so-called "Stress concentrating zone" as shown as the red bold line in Fig. 12. The b-value evaluation on the "Stress concentrating zone" should be modified based on the Gutenberg-Richter equation on seismic hazard of the region source in section 3.3. Fig. 13 shows the results of the b-value between the modified b-value model and exiting b-value model. From this figure, it is found that the b-value of the former model is larger than that of the latter model.

On the other hand, there are some "Earthquake blank zones" around the "Stress concentrating zone." The earthquake occurrence frequency evaluation at the "Earthquake blank region" shall be evaluated based on the non-Poisson process in section 3.3, such as the application to the occurrence frequency evaluation on the Nankai trench around Japanese islands [11].

5. CONCLUSION

The outlines of the seismic PSA implementation standards and seismic hazard evaluation procedure were shown. The overview of the cause investigation of seismic motion amplification on the NCO earthquake was also shown. Then, the contents for improving the seismic hazard evaluation methodology based on the lessons learned from the NCO earthquake were described as follows.

(1) It is very important to recognize the effectiveness of a fault model on the detail seismic hazard evaluation

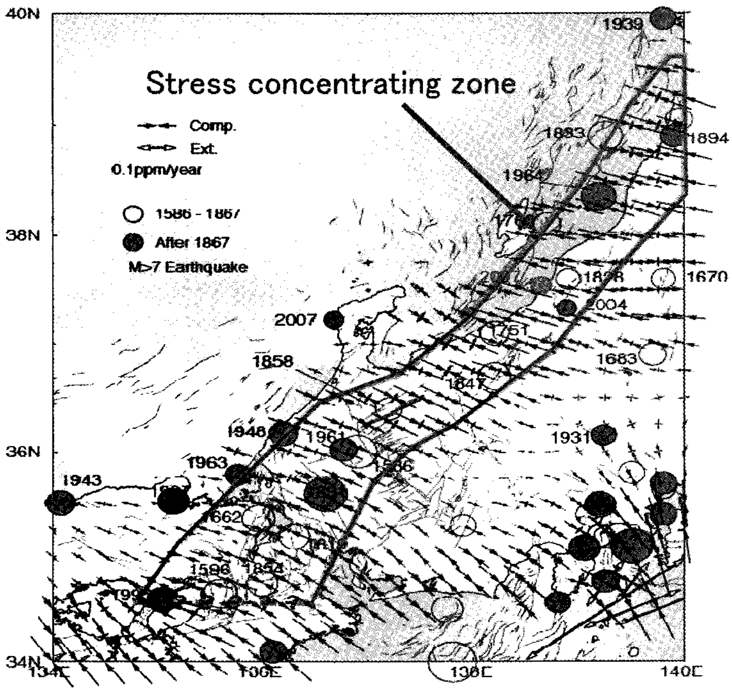

Fig. 12. Example of Stress Concentrating Zone around Niigata-ken Chuetsu-oki Earthquake

Table 3. Framework of the Open Deliberation Rule

(1) Uncertainty factors in determination of ground motion Ss are roughly classified into those in earthquake parameters and those in ground motion, and both of them are studied.
It is a common understanding that the final target is determination of the design basis ground motion necessary to structure design, not setting earthquake parameters.

(2) It is confirmed that there are two kinds of uncertainty factors; one is those which can be treated by probability, and the other is those which can not be expressed by probability such as difference of expert opinions.
It is re-confirmed that it is especially quite important to form consensus between experts regarding the latter factors.

(3) It is re-confirmed whether there are any effective methods other than logic tree method in order to quantify uncertainty or not. If there are none, then it should not be cloud but make clear whether to apply logic tree method.

(4) It is first priority to secure explanation-ability and transparency through whole deliberation process.
It is prohibited to make discussions only for the sake of discussion such as staying and hesitating on the way of the course from setting earthquake parameters to determination of basic ground motions.

(5) Sensitivity analysis on the factors proposed as expert opinions is performed timely on the way of logic tree formation and their contributions to basic ground motions are shown quantitatively. Factors with less contributions are left late without persistence and progress of deliberation should be promoted.
Technical issues are clarified concerning these factors with less contributions with leaving evidence, and commended to academic society and/or association.

(6) It is a common understanding that recent scientific knowledge and findings are utilized usefully, but that there is a possibility of facing a situation in which there is no way other than engineering judgment finally in the determination of basic ground motions.

(7) In a case that there occurs discussion how ground motion Ss influences the function of structures, reference information will be given. But emphasis is put persistently on the discussion of determination of ground motion.

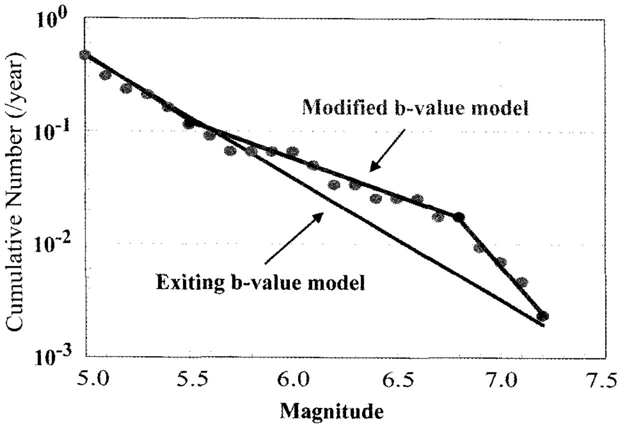

Fig. 13. Example of the Analysis Results of b-value by both Modified b-value Model and Exiting b-value Model at Stress Concentrating Zone

for near seismic source through the cause investigation of the NCO earthquake.

(2) In order to perform and proceed with the seismic hazard evaluation along the open deliberation rule, JNES has proposed the framework of the open deliberation rule regarding the treatment of uncertainty, which was made so as to be able to utilize a logic tree, referring to the formation of a logic tree of AESJ.

(3) The b-value evaluation on the "Stress concentrating zone," which is a high seismic activity around the NCO hypocenter area, should be modified based on the Gutenberg-Richter equation.

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