A DIALOGUE SCHEME BETWEEN SCIENTISTS AND ENGINEERS TO HANDLE DESIGN UNCERTAINTIES IN NUCLEAR POWER PLANTS

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ABSTRACT :

Importance of close collaboration among scientists and engineers is discussed based on experiences on seismic design guidelines for Nuclear Power Plants (NPP) in Japan. Following general aspects of the problem in the context of engineering decision uncertainties, some experiences are presented where collaboration among geophysical scientists and engineers were essential. These examples include discussion in the course of revision of the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities, publication of Standard for Procedure of Seismic Probabilistic Safety Assessment for NPP by Atomic Energy Society of Japan (AESJ Standard on PSA), JNES Workshop on PSA, and a JNES project on logic tree application to assessment of a major active fault.

KEYWORDS: nuclear power plants, design uncertainty logic tree, seismic PSA, mission mind

1. INTRODUCTION

In September 2006, the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities was revised for the Japanese nuclear power plants[1)]. The committee activities for development of the new guideline were where collaboration was truly needed between geophysical scientists and earthquake engineers. Such collaborations are more needed now as the design practice requires seismological as well as engineering clarification in highest caliber.

Engineering decision is inevitably subject to various sources of uncertainties as it must cope with the hazard occurring in the future. Design basis earthquake motion Ss for NPP is a typical issue of decision under uncertainty. They involve aleatory uncertainty (statistics) as well as epistemic uncertainty (modeling uncertainty). This leads to seismic PSA (probabilistic safety assessment) as a holistic approach to handle the issue.

No matter how deeply geophysical studies are cultivated, there are always variability in experts' opinion regarding the seismic activities in the future such as fault length and size, fault rupture mechanism and parameters, activity history and recurrence time, etc. Engineering judgment should be made with a notion of a range of ground motion intensity that is significant as to the risk of accidents (e.g., core melt down), which is another source of engineering uncertainties. Not only probabilistic models to deal with aleatory uncertainties, other methods for dealing with epistemic uncertainties are needed such as logic tree methods. With this kind of systematic ways of treating uncertainties, there is a possibility that seismologists and engineers can cooperate effectively.

With these notions, some practical examples of collaborative activities for seismic hazard modeling will be discussed. It will refer also to the methods of such synergetic actions recommended in recently authorized Atomic Energy Society of Japan (AESJ) Guidelines for the Seismic PSA for nuclear power plants.

2. IMPORTANCE OF COLLABORATION BETWEEN GEOPHYSICAL SCIENSE AND EARTHQUAKE ENGINEERING

A core mission of earthquake engineering is to design and construct engineered systems with sufficient levels of safety against natural hazards including earthquakes. The design process is inevitably subject to decision under uncertainty. Collaborative communication among geophysical scientists and earthquake engineers is indispensable in order to make appropriate hazard assessment. This notion is particularly important in the design of Nuclear Power Plants (NPP) whose safety is critically required in high-seismicity countries like Japan.

Earthquake motions to be experienced in future at NPP sites are estimated under combination of assessment of causative faults and assessment of ground motions. At this point, it is required that most updated scientific knowledge on tectonic geomorphology and strong motion seismology be mobilized where contributions from those scientists are essential.

Earthquake engineers, on the other hand, are responsible to offer an appropriate methodology for decision making on design earthquake motions. The methodology should include a rational process of treating design uncertainties. The decision under uncertainty must be practiced in an integrated framework of the hazard uncertainties and reliability of engineering systems. A holistic way is practicing seismic probabilistic safety assessment (seismic PSA) of the entire NPP system. Deterministic design ground motion should be consistent with this framework of uncertainty treatment.

In order to establish good collaborative relations between geophysical scientists and earthquake engineers, each other's roles must be understood and respected mutually. Science pursue the "truth of the natural mechanism". Engineering uses knowledge on natural mechanism for "human well being." They certainly share ample common regions. Engineering objectives will not come true without deep understanding of the nature as the source of hazard. Scientific activities often raise warning to the society based on scientific findings. But it is natural that different purposes result in different methodologies. One distinct difference is seen in the treatment of uncertainties.

Uncertainties associated with scientific research are normally regarded as random errors or consequences of unknown mechanism of the nature. The level of uncertainty is not necessarily a critical issue in scientific clarification. It shows "how sure we are about the explained facts." They may be shown by statistical measures like standard errors, but they are often stated qualitatively.

In engineering practice, quantitative assessment of design uncertainties is a solid requirement, as the role of engineering is to cope with earthquakes that will occur in the future. Here, "decision under uncertainty" is inevitable. In defining deterministic values for design parameters, various sources of uncertainty should be analyzed and integrated in a consistent systematic approach. The sources of uncertainty consist of aleatory uncertainties (random sources) and epistemic uncertainty (imperfect modeling). While aleatory uncertainties can be treated using probability theory, epistemic uncertainties need other methods such as logic trees. Such situations can be seen in the interpretation of scientific data on active faults. For example, the Itoigawa-Shizuoka Tectonic Line, one of the major Japanese active faults, is most extensively investigated in terms of geophysical exploration. Yet there are various opinions among geophysical scientists regarding its segmentation and period of previous activities. This type of uncertainty should be treated properly in the engineering design decision process.

It was common practice in the past design process for Japanese NPP's to exclusively adopt one of different opinions on fault assessment. Such a case can be seen in the design of Kashiwazaki-Kariwa NPP which was affected by the Niigata-Chuetu-oki Earthquake of 16 July 2007. This earthquake was caused by a sea-bottom active fault whose possibility was pointed out on the basis of geophysical sounding but not adopted in actual design. Uncertainty arising from this type of qualitative judgment is drawing attention to pursue rational decision processes. This is where geophysical science and engineering should be tied more closely than before.

3. SCIENSE AND ENGINEERING IN REVISION OF THE REGURATRY GUIDE FOR REVIEWING SEISMIC DESIGHN OF NUCLEAR POWER REACTOR FACILITIES

In September 2006, the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (abbreviated as Seismic Design Reviewing Guide) was revised by the Nuclear Safety Commission (NSC) of

Japan[2]. The major purpose of the revision was to incorporate advancements in seismology and earthquake engineering in the past two decades. The mission was an administrative purpose of seismic safety regulation. But it has to be formulated on a sound scientific basis. During the committee meetings, there were tremendous amount of scientific discussion and debate on the methodology of seismic hazard assessment and decision of design basis earthquake motion Ss. New features of the revised Guide regarding decision uncertainties in seismic hazard may be summarized as follows.

a) Definition of potential earthquake sources: Not just "active faults" but more general tectonic geomorphology including and active folding / active flexure. The period range was extended to Upper Pleistocene.
b) Hazard from unidentified sources: While the previous Guide defined an M=6.5 earthquake at the distance of 10km, the revised Guide defines a method based on near-field strong motion records. It also refers to a PSHA approach.
c) Consideration of uncertainty in determining Ss: It is explicitly stated that uncertainties associated with decision of Ss should be appropriately considered. It is followed by a statement that the annual probability of excedence of design response spectra based on the defined Ss should be referred to in the process of licensing discussion.
d) Recognition of "residual risk": Needs for considering cases where the design basis earthquake motion Ss be exceeded in actual earthquakes was explicitly stated. It opens a roadway to incorporate the concept of "residual risk" arising in design decisions. The seismic PSA is stated as a major methodology to deal with the issue, but not enforced in this stage of the Guideline.

Among the four issues stated above, 1) is geophysical science based issue, while 2) - 4) are engineering oriented issues, since rational treatment of uncertainty is required. It should be emphasized that in all aspects, collaboration among geophysical scientists and engineers are essential. This notion is now widely recognized among experts in NPP safety. and regulatory discussions.

4. TREATMENT OF EPISTEMIC UNCERTAINTY IN SEISMIC HAZARD ASSESSMENT FOR NPP

Epistemic uncertainty require most careful treatment among various sources of design decision uncertainties, as their original information is often provided as qualitative statements representing experts' opinions. Efforts have been taken since mid 90's in Japan for quantitative evaluation of epistemic uncertainties in seismic hazard assessments in the context of seismic PSA of NPP. The logic-tree scheme is commonly used as a major tool for dealing with epistemic uncertainty. US activities are forerunners in this field. The methodology was needed particularly in moderate or low seismicity areas in the central and eastern US where interpretation of geophysical survey data but with sparse record of earthquake occurrences was a critical issue. SSHAC report[3] is a typical document where the use of logic trees was implemented.

It should be noted, however, treatment of epistemic uncertainties should be important as well in high seismicity areas like Japan. No matter how plenty geophysical information and strong motion data we may have, it is extremely difficult to establish a single fixed image of earthquake motions to occur in future. Here the uncertainty involves not only aleatory uncertainty (statistics) such as strong motion attenuation uncertainties but also epistemic uncertainty (modeling interpretation) ranging among geophysical scientists regarding the size and segmentation of active faults, source mechanism of future earthquakes, recurrence of fault activities, etc., which are all very important design parameters for NPP.

With this recognition, NUPEC/JNES efforts were conducted under a national project (R&D on Seismic PSA for Nuclear Facilities in Japan) to formulate an integrated method for treatment of uncertainties incorporating probability models and logic trees[4]. Based on this activity, JNES performed probabilistic seismic hazard analysis (PSHA) for four Japanese NPP sites. How to integrate different opinions among geophysical scientists was a key issue, where logic tree was used as a core method. An example is shown in Figs.2-4. the site (referred to as Site 4) is located near the western part (about 100km) of the Mean Tectonic Line (MTL) whose total length is over 300km. Fig.2 shows diversity of experts' opinion on segmentation of the fault. Fig.3 shows a part of the associated logic tree. Fig.4 shows the results of seismic hazard assessment.

The JNES workshop on seismic hazard entitled "Workshop on How to Overcome Uncertainties in Seismic Hazard Assessment -Application of Logic Tree-", Tokyo, April 2004 was a turning point from the research phase to an implementation phase[5]. The workshop discussion have enhanced recognition not only among researchers but also among practitioners and regulatory officials that assessment of epistemic uncertainty is indispensable, that logic tree is useful, and that constructing good logic trees is more important than their quantification

These efforts were incorporated in Standard for Procedure of Seismic Probabilistic Safety Assessment (PSA) for Nuclear Power Plants[2)] published by the Atomic Energy Society of Japan (AESJ) in September 2007. The AESJ Standard is a comprehensive document covering the context issues and methodological details of seismic PSA for NPP. While the seismic PSA development has a history of two decades in Japan, treatment of epistemic uncertainties and use of logic trees was explicitly stated as a major element of seismic PSA for the first time in this type of authorized document. The framework of integrating experts' opinions, particularly the roles of TF (technical facilitator) and TFI (technical facilitator-integrator) basically conforms with the SSHAC Report[3)], but with a modification to reduce the original four-level scheme to a three-level considering the high seismicity throughout Japan.

5. RECENT JNES ACTIVITY ON ENGINEERING JUDGMENT BASED ON INFORMATION OF GEOPHYSICAL SCIENTISTS

With a notion of the new AESJ Standard on Seismic PSA, a task team was organized by JNES to apply the AESJ Standard with a focus on the logic-tree based assessment of active fault[6)]. In order to highlight the importance of the methodology in the Japanese seismic environment, the Itoigawa-Shizuoka Tectonic Line (ISTL) was selected as the object of analysis. It is a major active fault, and is one of the best-documented faults in Japan. It was the purpose of the Task Team to demonstrate that even such a well-documented fault needs consideration of epistemic uncertainty and to practice its treatment based on the new AESJ Standard.

The Task Team consisted of six geophysical scientists (experts in active faults, geology, and strong motion). One of them acted as TFI (technical facilitator-integrator). Plus this, an engineer played a role of "supervisor" in cooperation with TFI in order to orient the activities to converge to logic tree information that is scientifically acceptable and useful for engineering decision.

The team met six times in a period of one year, where discussion was conducted on the characteristics of ISTL including dip angle, activities, recurrence interval, minimum segments, linked range, etc. Fig.6 shows diversity of experts' opinion that was made clear through the discussion sessions. On this basis, a logic tree for interpretation of ISTL as shown in Fig.7. PSHA was performed for each path of the logic tree that lead to a fractal set of hazard curves. The process and the results of the activity was convincing regarding the effectiveness of the scientists and engineers.

6. CONCLUDING REMARKS

This paper discussed desirable scheme of collaboration between scientists and engineers in earthquake engineering practices. It was emphasized that engineering decisions are inevitably "decision under uncertainties" so that systematic and quantitative treatment of uncertain design parameters is important. Discussion was focused on seismic hazard assessment for the design of nuclear power plant (NPP) which requires maximum level of seismic safety. It was clarified that despite the differences between the purposes of geophysical science and earthquake engineers their collaboration is indispensable for geophysical clarification and engineering treatment of uncertainties.

Several practical cases were presented where design uncertainties play key roles. These cases include implementation of design uncertainties in the revision of Seismic Design Reviewing Guide (effective 2006), treatment of epistemic uncertainties for quantification of experts' opinions in geophysical science based on activities at NUPEC/JNES and AESJ, and JNES efforts dealing with ISTL.

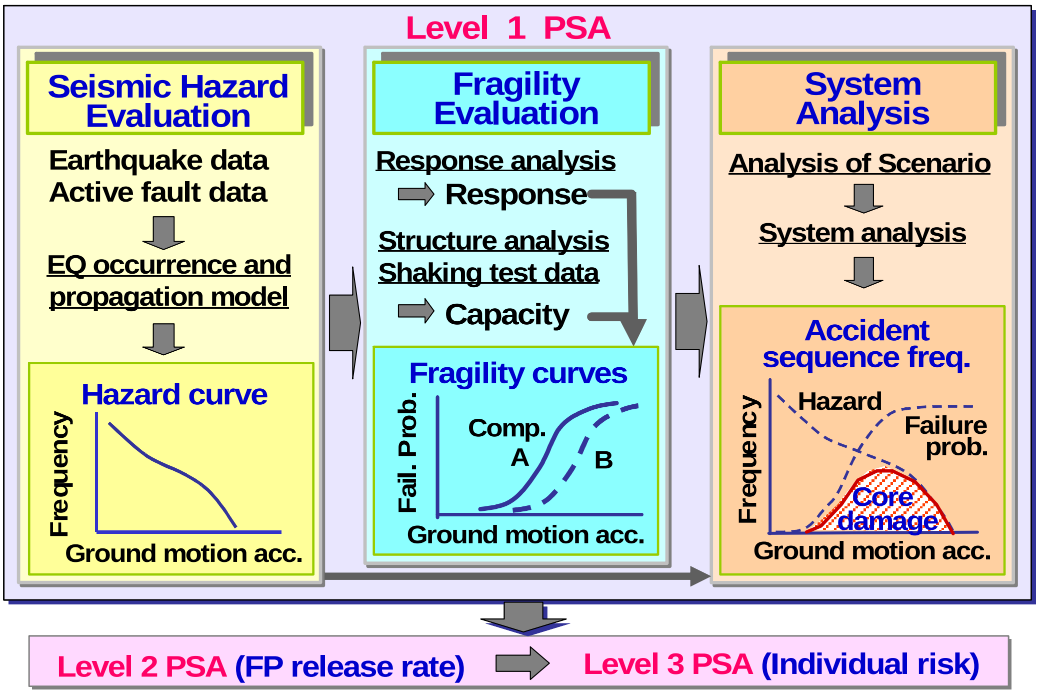


Fig.1 Procedure of Seismic PSA

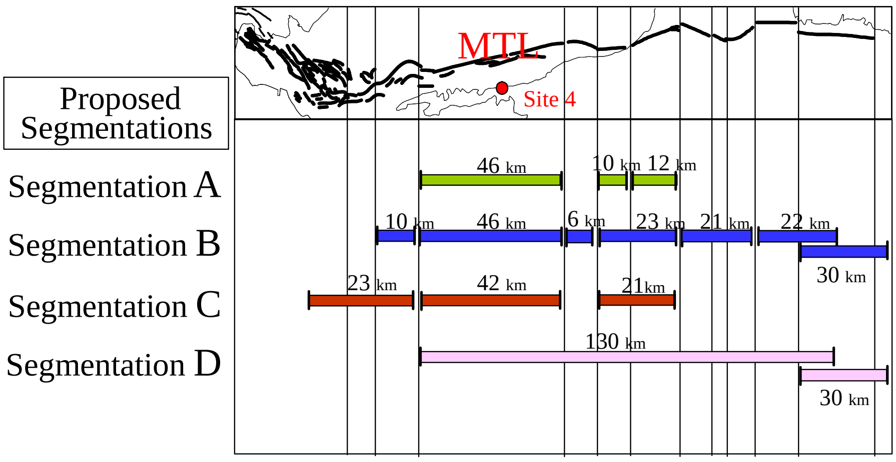


Fig.2 Proposed Segmentation of MTL (Mean Tectonic Line)

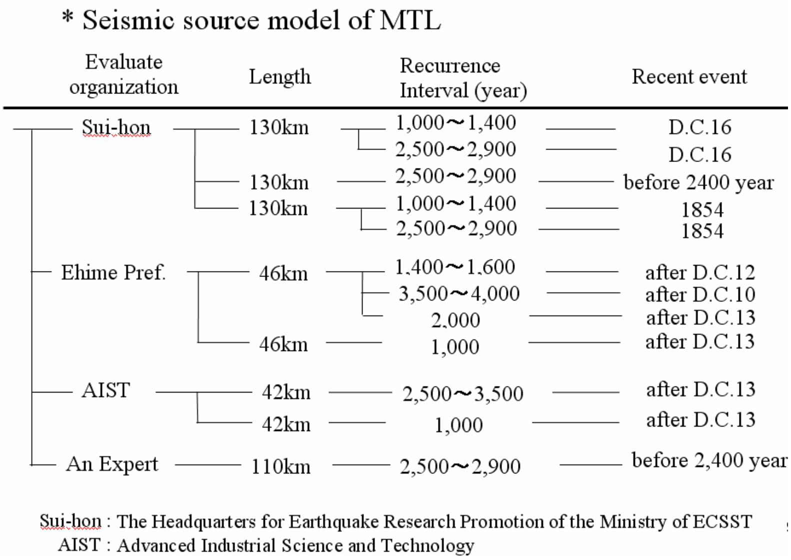
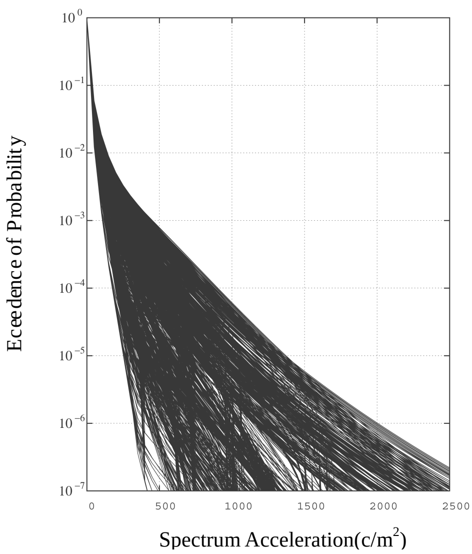
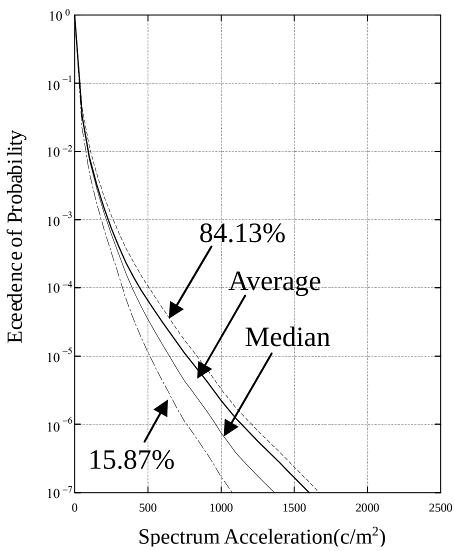


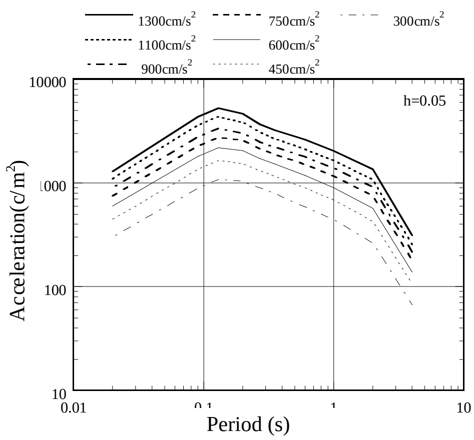
Fig.3 Logic Tree for Site 4



(a) Seismic Hazard of Each Path of LT



(b) Seismic Hazard



(c) Uniform Hazard Spectrum

Fig.4 Seismic Hazard of Site 4

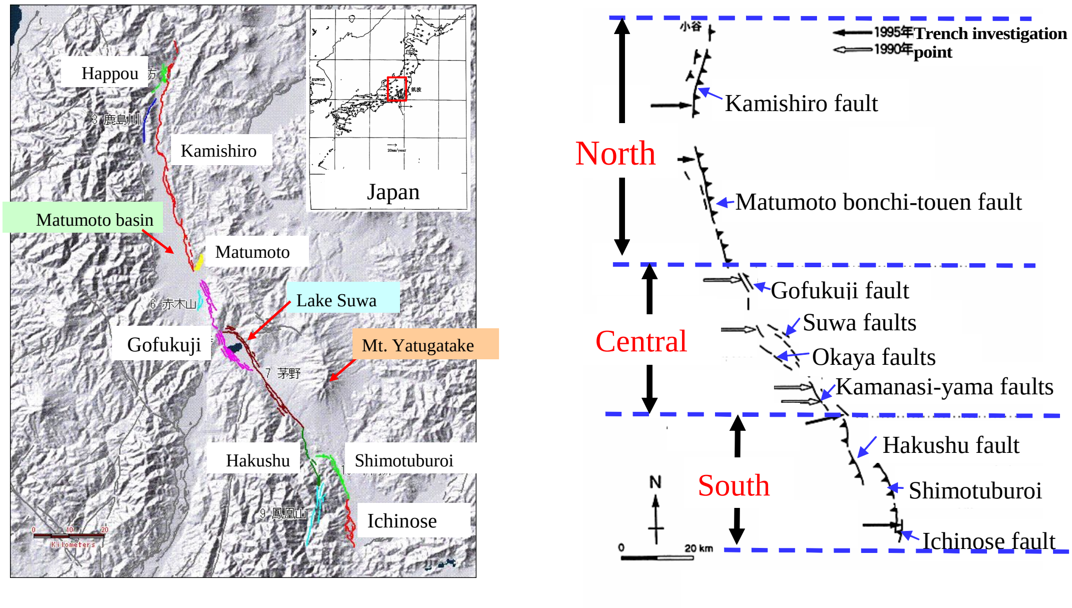
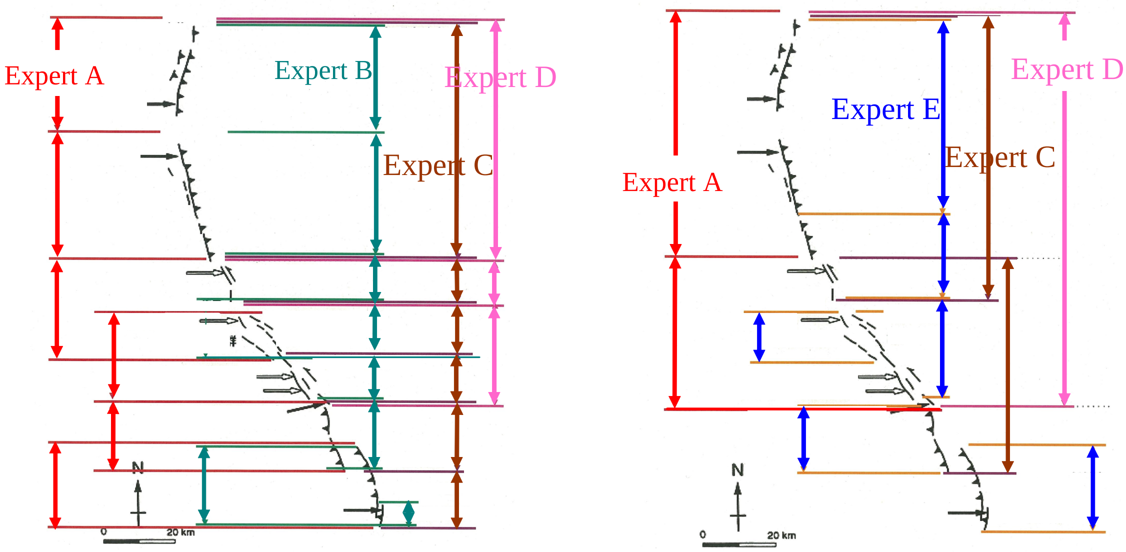


Fig.5 Itoigawa-Shizuoka Tectonic Line (ISTL)



Minimum Range of Active Fault
(Active Segment)

Linked Range of Active Faults
(Segmentation)

Fig.6 Example of Experts Judgment about ISTL

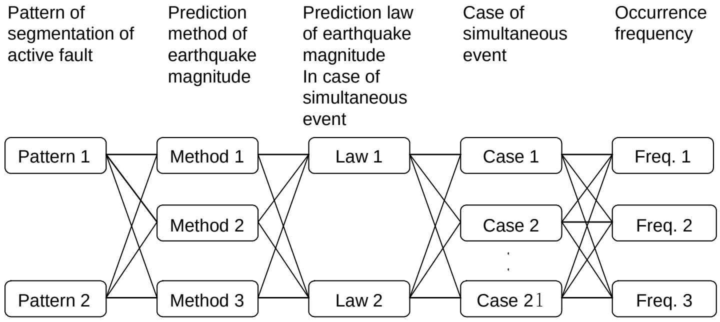


Fig.7 Logic Tree of ISTL

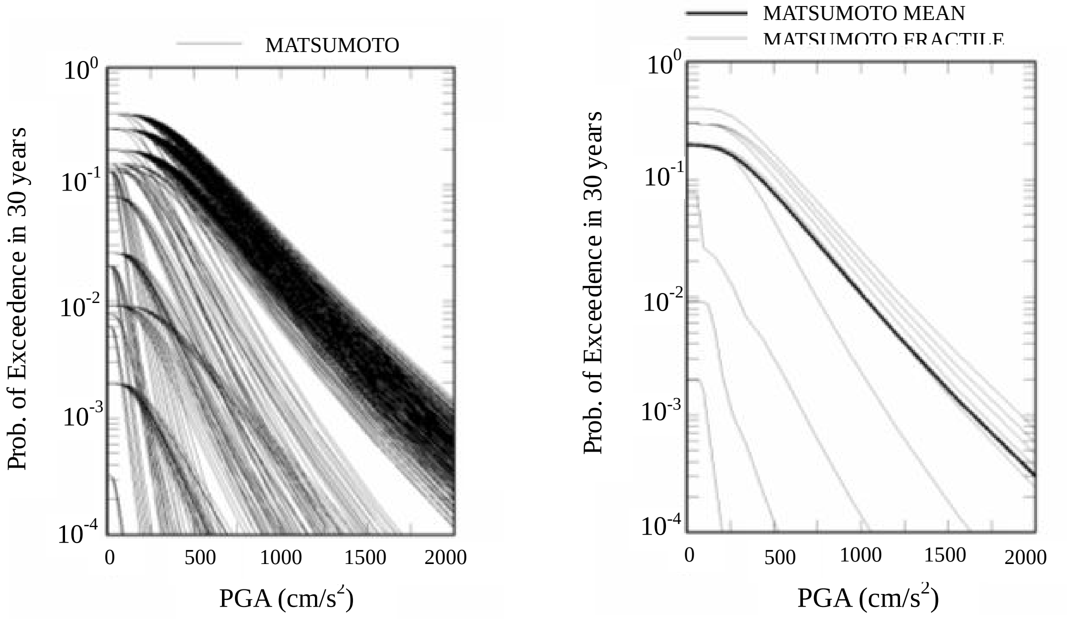


Fig.8 Seismic Hazard Curve of ISTL

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