Development of Evaluation Method for Probabilistic Seismic and Tsunami Hazards Considering Events Superimposition

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An integrated evaluation method for superimposed seismic and tsunami hazards is discussed in this paper. In general, probabilistic seismic hazard analysis (PSHA) and probabilistic tsunami hazard analysis (PTHA) is conducted independently in a case where earthquake and tsunami are identified as key external events to be considered at a target site/region. However, independent analyses for probabilistic seismic and tsunami hazards are not sufficient because tsunami is physically caused by earthquake occurrences (namely fault plane dislocations) and we must consider the law of causality in evaluating seismic and seismic-induced tsunami hazards in an integrated manner

I. INTRODUCTION

Although large number of studies on multi-hazard assessment has been conducted, events superimposition among external events were not considered. However, an enhanced method is necessary for a site or region where not a single hazard but multi-hazards should be considered.

Current status of PRA (Probabilistic Risk Assessment) provides a starting point to discuss this issue as shown in Fig. 1. In performing Seismic PRA of critical facilities, we need information on seismic hazard curve which can be obtained by conducting probabilistic seismic hazard analysis. As same as Seismic PRA, tsunami hazard curve at a target site or a control point is necessary in performing tsunami PRA, and tsunami hazard curve can be computed by conducting probabilistic tsunami hazard analysis. PSHA (Ref.1, 2) and PTHA is generally conducted independently in a case where earthquake and tsunami are identified as potential key external events at a target site/region. However, independent analyses for probabilistic seismic and tsunami hazards are not sufficient because most of tsunami is physically caused by earthquake occurrences (namely fault plane dislocations). This leads to that we must consider the law of causality existing among external events occurrence in multi-hazards assessment.

Seismotechtonics of Japan is complicated compared to other regions/countries, and all types of earthquakes, that are crustal earthquakes, interplate earthquakes, intraplate earthquakes including slab earthquakes and outer-rise earthquakes, must be considered in seismic hazard assessment. Moreover, interplate earthquake with large magnitude (greater than 8) can occur aperiodically and cause large and destructive tsunami. The 2011 off the Pacific coast Tohoku Earthquake of M_w 9.0 caused intensive ground motion and large tsunami, and enormous lives were lost and many structures and facilities were damaged heavily.

The purpose of this paper is to develop a quantitative method for probabilistic seismic and tsunami hazards considering event superimposition. The output of the study can be applied as an input for performing PRA against superimposed earthquake and tsunami.

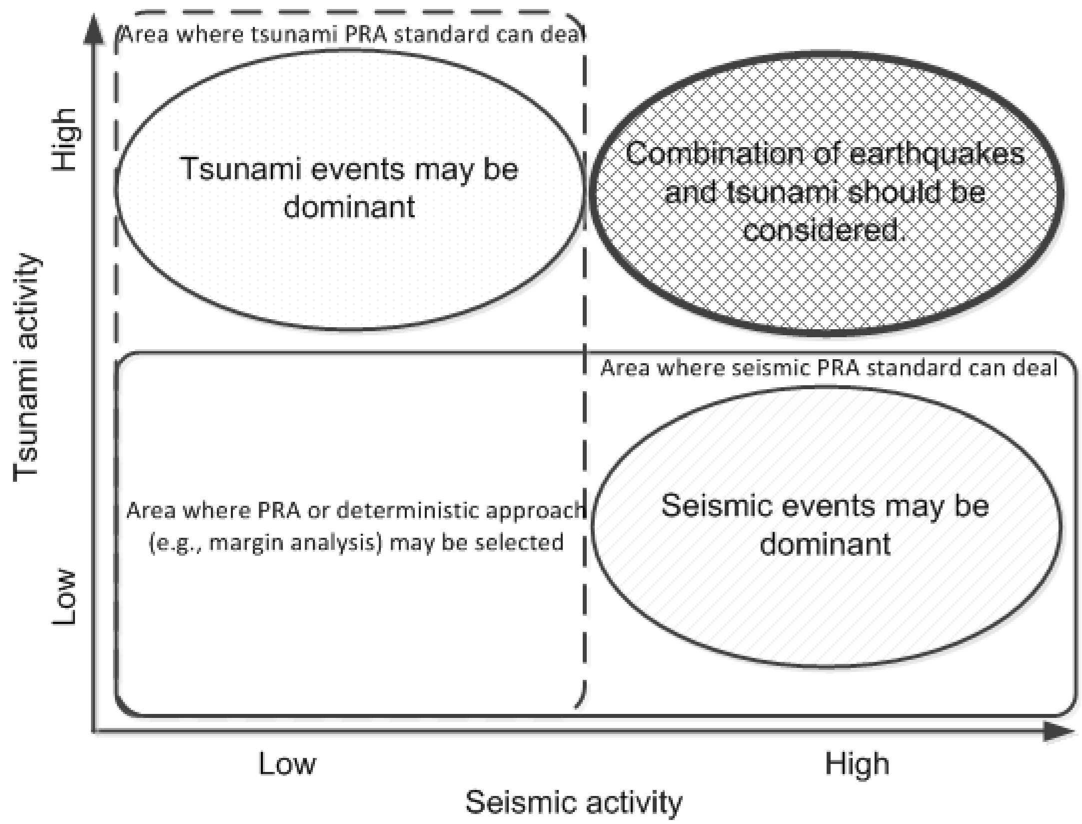

Fig. 1. Scope of this research: area where multi-hazards evaluation is necessary from the viewpoint of safety assessment for critical facilities

II. Key Issues in Multi Hazards Evaluation

Although a large number of studies has been made on multi hazards evaluation, little is known about development of multi-hazards evaluation in a case where one hazard is caused or effected by the other. Fig. 1 shows a scope of this research from the viewpoint of safety assessment for critical facilities. Conventionally, a single hazard is focused in safety or risk assessment of critical facilities. If we evaluate earthquake is dominant as external natural phenomena at a site, we assess the safety/risk of a target structure, facility by Seismic PRA or SMA (Seismic Margin Analysis).

In general, PSHA and PTHA are conducted independently, and seismic hazard curves and tsunami hazard curves are computed respectively. However, most of tsunami is physically caused by earthquakes, that is dislocations of fault planes, and it occurs after earthquake. This means that we must consider the law of causality in evaluating seismic and tsunami hazards in an integrated scheme.

II.A. Mathematical Formulation

A fundamental methodology and scheme was developed by Cornell (Ref. 1). Hazard surface of earthquake and tsunami is calculated by enhancing the Cornell's formulation as following equation:

$$P(Y \geq y \; and \; H \geq h | Y \geq y; t) = 1 - \prod_{k=1}^{L} \{1 - P_k(Y \geq y \; and \; H \geq h; t)\}$$
$$= 1 - \prod_{k=1}^{L} \left[\sum_{n=0}^{\infty} P_k(E_{k\_n}, t) \{1 - P_k(Y \geq y \; and \; H \geq h)\}^n \right] \quad (1)$$

, where *Y* and *y* are seismic ground motion level, *H* and *h* are tsunami wave height level, *t* indicates unit period of time for hazard analysis (e.g, 1 year, 30 years). E_k denotes an event of earthquake occurrence in source *k*, and *n* is the number of earthquake occurrence during *t*.

II.B. Consider Aftershock

In general, only mainshocks are considered as earthquake occurrence events in conducting PSHA. However, we must model the maximum-magnitude aftershock as one of seismic source characterization in a case where the mainshock magnitude exceeds nine. By combining the Gutenberg-Richter equation and modified Ohmori formula, the number of aftershocks and occurrence is computed respectively as follows (Ref. 7):

$$\nu(t) = \frac{K}{(t+c)^p} \quad (2)$$
$$\log \nu_{AS}(M_{AS}|M_{MS}) = \frac{a_{AS} - b_{AS} \cdot M_{AS}}{a_{MS} - b_{MS} \cdot M_{MS}} \quad (3)$$

The probability that aftershock with magnitude *M* to *M* plus *dM* will occur in the time interval from *T* to *T* plus *dT* is computed from the following equation:

$$Q = 1 - \exp\left\{ - \int_{T_1}^{T_2} \Lambda(M, s) ds \right\} = 1 - \exp\{-N(T_1, T_2)\} = 1 - \exp[-K\exp\{-\beta(M - M_{th}) \cdot A(T_1, T_2)\}]$$
$$= 1 - exp\left[\frac{-Kexp\{-\beta(M - M_{th})\}}{1 - \rho} \cdot \left\{ \frac{1}{(T_2 + c)^{p-1}} - \frac{1}{(T_1 + c)^{p-1}} \right\} \right] \cdots (p \neq 1) \quad (4)$$
$$= 1 - \exp[-Kexp\{-\beta(M - M_{th})\}\{ln(T_2 + c) - ln(T_1 + c)\}] \cdots (p = 1) \quad (5)$$

where M_{th} denotes minimum magnitude of aftershocks adopted for the Gutenberg-Richter equation or Modified Ohmori formula.

III. Method to Evaluate Seismic and Tsunami Hazards Considering Events Superimposition

In this chapter, the procedure of the discussed method is outlined. The method consists of five steps as shown in Fig.1, and the details of each steps is addressed hereafter.

Step 1: Construct a reginal seismo- and tsunami-techtonic models

Seismic sources and tsunami sources are constructed based on comprehensive and integrated data and knowledge of seismology, geology, geophysics and seismo-tetonics.
What has to be noted that seismic sources and tsunami sources should be modelled identically as much as possible.

Step 2: Conduct probabilistic seismic hazard analysis.

GMPE (Ground Motion Prediction Equation) is basically adopted in order to estimate seismic ground motion level from each seismic source. In the method we develop, fault rupture model are adopted in assessment of earthquake ground motion in a case where seismic source with large magnitude which exists in near filed to a site is dominating its seismic hazard. In general, fault rupture models are classified into four models:

- Stochastic model
- Asperity source model
- Hybrid source model
- Composite source model

A selection of the model/technique depend upon data and knowledge of the target source.

Step 3: Conduct hazard de-aggregation/dis-aggregation

(a) Conduct seismic hazard dis-aggregations at multiple-points, specifically short to long periods of earthquake ground motions that is one of GMPE's parameter. (b) Compute hazard-consistent ground motion waves for each source

Step 4: Conduct probabilistic tsunami hazard analysis

PTHA is conducted following the procedure by Refs. 4, 5 and 6 for dominant source which are objectively identified in Step 3. Non-seismic induced tsunami is also assessed in this step.

Step 5: Compute Joint Hazard Surface of Earthquake and Tsunami

Hazard surface of earthquake and tsunami can be generated by following Eq. (1): that integrates output of Step 2 and Step 4.

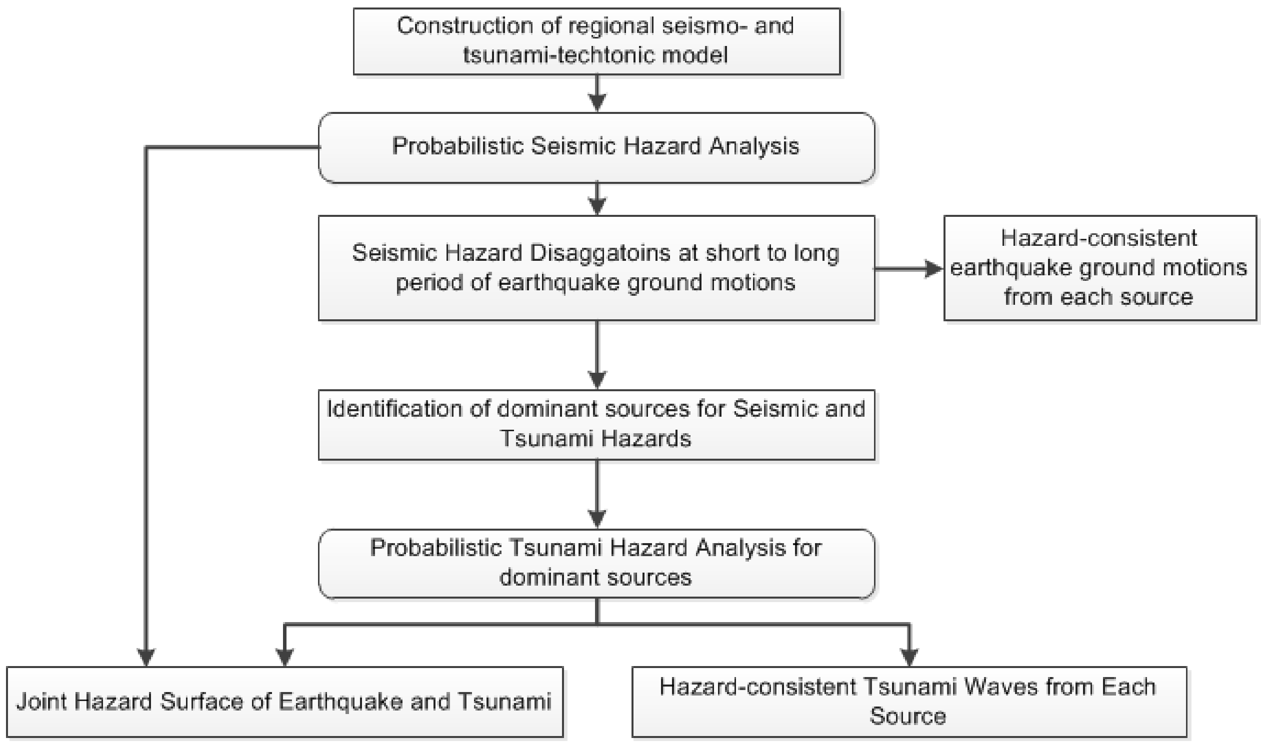

Fig. 2. Flowchart of evaluation method for seismic and tsunami hazard

IV. Numerical Simulation

To illustrate a specific characterizations of seismic and tsunami hazards evaluations discussed in the previous section, we conduct numerical simulation. Problem settings for performing numerical simulations are addressed below.

IV.A. Site and Region

A site is chosen, which is located in Tohoku region Japan. The reason why this area is selected is that both seismic and tsunami activity is high even in Japan, and the 2011 Tohoku Great Earthquake hit this area.

IV.B. Source Characterization of Earthquake and Tsunami

Seismic sources are modelled mainly based on information published by the Headquarters for Earthquake Research Promotion of Japan. However, the following two points are different from the Headquarters for Earthquake Research Promotion of Japan's model:

- b-value of Gutenberg-Richter equation: b-value of the Gutenberg-Richter equation is calculated based on earthquake catalogue in each source. This means that b-value might vary according to each source.
- As is described in II.B., seismic hazard by aftershocks are also evaluated based on the Headquarters for Earthquake Promotion Research Promotion's model (Ref. 8), which represents by Eqs. (2)(3)(4) and (5).

Fig.3 shows fault planes locations of one interplate earthquake which occur along the Nihon Trench.

Considering historical and prehistorical data, tsunamigenic sources are modelled based on the following policy:

- Near and intermediate tsunamigeneic sources are modelled based on the seismic sources: this means that the tsunamigenic sources are mostly identical to seismic ones,
- Far tsunamigeneic sources are additionally modelled, which is capable of causing tsunami although they are not modelled as seismic sources due to low sensitivity to the seismic hazard at a target site,
- Seismic sources are modified to represent tsunamigenic source in a case where areas of seismic and tsunamigenic sources are partially overlapped.

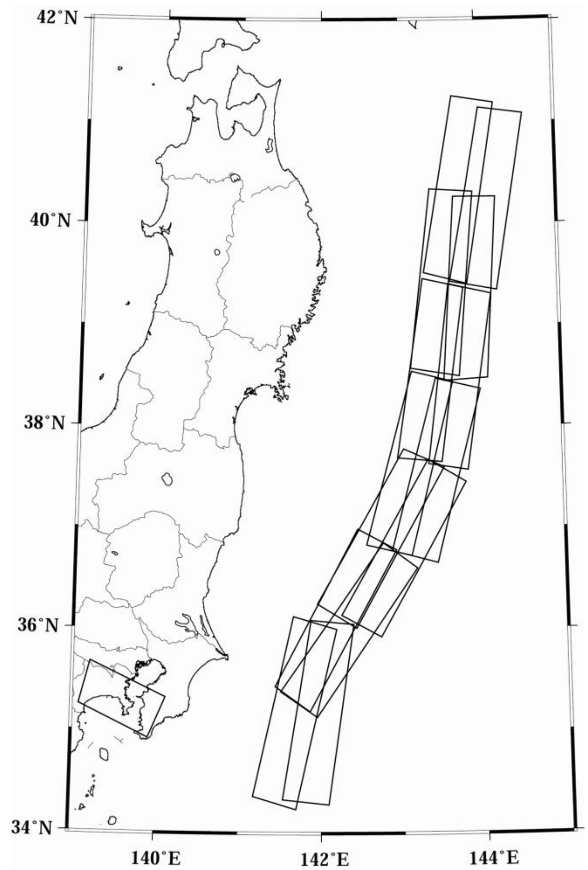

Fig. 3. Map of the model region and site for numerical simulation: rectangle in the figure denotes examples of fault planes of interpolate earthquake models

IV.C. Ground Motion Characterization

In this numerical simulation, GMPE developed by Nishimura et al. (Ref. 13) is adopted to predict earthquake ground motion level from each source.

$$\log S_A(T) = a(T)M_J - \{b(T)X_{eq} + \log X_{eq} + c(T)\} \quad (6)$$

where S_A(T) denotes mean of response acceleration (cm/s^2), and M_J denotes JMA (Japan Meteorological Agency) Magnitude and X_{eq} denotes the equivalent hypocentral distance developed by Ohno et al. X_{eq} is calculated from the following equation:

$$\frac{1}{X_{eq}^2} = ln\left\{1 + \left(\frac{R}{X}\right)^2\right\}\frac{1}{R^2} \quad (7)$$

$$\mathrm{R} = 10^{0.5M-2.28} \quad (8)$$

where X is a site-fault plane center distance, and $a(T), b(T)$ and $c(T)$ denotes a constant corresponding to a period $T(s)$.

In a case where a seismic source which is located very close to a site is dominant, ground motion is evaluated by using fault rupture models instead of GMPE. As is addressed in IAEA Safety Report No. 86 (Ref. 14), various kinds of fault rupture models have been developed, and there does not exist an aggregable rule how the fault rupture model can be incorporated in PSHA at the present time. Considering the current status, stochastic model and asperity models are considered as candidate models in this study although we don't intend to exclude the hybrid source models (e.g., Ref. 9).

IV.D. Probabilistic Seismic Hazard Analysis

We adopt and follow the procedure of probabilistic seismic hazard analysis which was originally developed by Cornell (Ref. 1) and has been enhanced by SSHAC (Ref. 2) and AESJ (Ref. 3). As for hazard deaggregation, we basically adopt and incorporate a method which has been developed by Kameda and Ishikawa (Ref. 15), in this research. Earthquake occurrence of each source is modelled based on information on the historical earthquake events. In a case where there are sufficient data on past earthquake events or evidences, occurrence in time domain is modelled based on theoretical probability distribution such as BPT (Brownian Passage Time) distribution (Ref. 11) and other model (Ref. 12) which follows a renewal process.

IV.E Probabilistic Tsunami Hazard Analysis

Probabilistic tsunami hazard analysis is conducted by following a procedure provided by US.NRC (Ref. 4), IAEA (Ref. 5) and AESJ (Ref. 6). Some steps which consists of PTHA are enhanced based on the latest research output (e.g., Ref. 10)

IV.F. Joint Surface of Seismic and Tsunami Hazards

Jointed probability which exceeds a certain earthquake ground motion and tsunami height levels can be computed from the Eq. (1) derived in II.A.

The results of numerical simulations will be presented at the conference.

V. Discussions

Regarding the technical issue which characterized the method developed, It cannot be discussed here lack of numerical simulation results as illustration. So, let us now attempt to discuss from the viewpoint of idea itself and procedural aspects. The method we discussed can evaluate seismic and tsunami hazards in an integrated manner, and this makes it possible to evaluate uncertainties more logically and accurately. Furthermore, this method has the advantage of enhancement in the following points:

- More detailed information on ground motions, tsunami wave can be incorporated in hazard evaluation if it is necessary because source characterization parameter can be computed via hazard deaggregation,
- Fault rupture model is incorporated in seismic hazard evaluation.

Numerical simulation results and key issues to overcome will be addressed in the presentation.

II. CONCLUSIONS

A method which makes is possible to evaluate superimposed seismic and tsunami hazards is developed. One of key issue is that we must consider the law of causality in evaluating seismic and seismic-induced tsunami hazards in an integrated manner. The method developed has the advantage that seismic and tsunami at a site can be evaluated in a sequential and integrated manner, and underestimate or overestimate of uncertainties can be solved. This method is especially necessary to evaluate seismic and tsunami hazards at a site/region where both seismic and tsunami activity are high.

There is room for further investigation and discussion on modelling seismic and tsunami sources in identical manner, although it does not harm the methodology

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