Probabilistic Seismic Hazard Analysis with Focus on Fourier Amplitude and Group Delay Time

T. Nagao
National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport, Japan

M. Yamada
Newjec Inc., Japan

A. Nozu
Port and Airport Research Institute, Japan

SUMMARY:
We propose a new framework for probabilistic seismic hazard analysis that enables to directly calculate the time history waveforms of ground motions corresponding to arbitrary annual probability of exceedance taking account of seismic source characteristics, propagation path characteristics and the ground motion amplification characteristics of deep subsurface profiles. The proposed method does not use representative values such as maximum accelerations and response spectra for calculating time history waveforms, but focuses on Fourier amplitude spectra and group delay times to directly determine the waveforms using a stochastic Green's function method, taking advantage of the linearity of operation among those characteristics. An application of the method to the sites in eastern Japan region is illustrated considering the effect of the 2011 off the Pacific coast of Tohoku Earthquake to seismic hazard.

Keywords: Seismic hazard analysis, stochastic Green's function method, uniform hazard Fourier spectrum

1. INTRODUCTION

Since the 1995 Hyogoken-Nanbu Earthquake, technical standards of Japanese civil engineering works apply two input seismic ground motion levels: Level 1 seismic ground motions and Level 2 seismic ground motions.

Level 2 seismic ground motions are defined as the ground motions with maximum-level intensities that may occur at the site of interest over time from the present to the future. On the other hand, Level 1 seismic ground motions are ground motions that may occur once or twice in the lifetimes of structures. Therefore, we need to use a probabilistic seismic hazard analysis in order to evaluate Level 1 seismic ground motion for each site of interest. This study discusses the method for evaluating probabilistic earthquake ground motions as time history waveforms.

Time history waveforms calculated through probabilistic seismic hazard analyses generally correspond to the hazard curves of the maximum accelerations or the acceleration response spectra obtained through the analyses. The effects of seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles are not necessarily taken into account in detail in such cases.

We propose a new framework for probabilistic seismic hazard analyses focusing on Fourier amplitudes and group delay times. Regarding the Fourier amplitude spectra and the group delay times of seismic ground motions, the linearity of operation holds among those characteristics. By using Fourier amplitude spectra and group delay times instead of representative values such as maximum accelerations and response spectra, those characteristics can be easily taken into account in detail.

2. CONVENTIONAL PROBABILISTIC SEISMIC HAZARD ANALYSIS AND ITS MAJOR PROBLEMS

Before describing our proposed probabilistic seismic hazard analysis, we outline a conventional seismic hazard analysis for calculating time history waveforms and discuss its problems.

2.1. Conventional Seismic Hazard Analysis

Figure 1(a) shows the flow of a conventional method for deriving the seismic hazard curves of the maximum accelerations and the acceleration response spectra of seismic ground motions.

2.1.1. Modeling of Seismic Sources

The first step is to model the seismic sources expected to cause earthquakes near the site of interest in the future. The modeling here means the setting of hypocentral distances. This is done by using earthquake catalogs, which are compilations of past earthquake records, to gather data on earthquakes that have occurred near the site of interest or by using data on active faults obtained through topographical and geological surveys.

When using earthquake catalog data, engineers either set one seismic source in each of equally divided meshes over a zone where seismic activities are uniform (hereafter called earthquake province) or set seismic sources randomly in an earthquake province. When using active fault data, engineers equally divide each active fault into several parts, and either use the distance from each subfault to the site or use one representative distance from the fault to the site. In either case, the seismic source locations (hypocentral distances) are specific to each active fault.

2.1.2. Assessment of the Sizes and the Occurrence Rates of Earthquakes

After the modeling of seismic sources, the engineers assess the sizes (magnitudes) and the occurrence rates of the earthquakes that may occur at these sources in the future.

When using earthquake catalog data, the engineers assume a model (b-value model) satisfying a Gutenberg-Richter's relation, which states that the logarithm of the occurrence rate of the earthquake (N) is proportional to the magnitude (M). Earthquake sizes are determined by randomly sampling the magnitude values in the size-wise occurrence rate distributions calculated from the model. Assuming that the occurrence of the earthquake follows a Poisson process, the occurrence rate at an earthquake province can be determined from the number of earthquake occurrences and the observation period recorded in the earthquake catalog data.

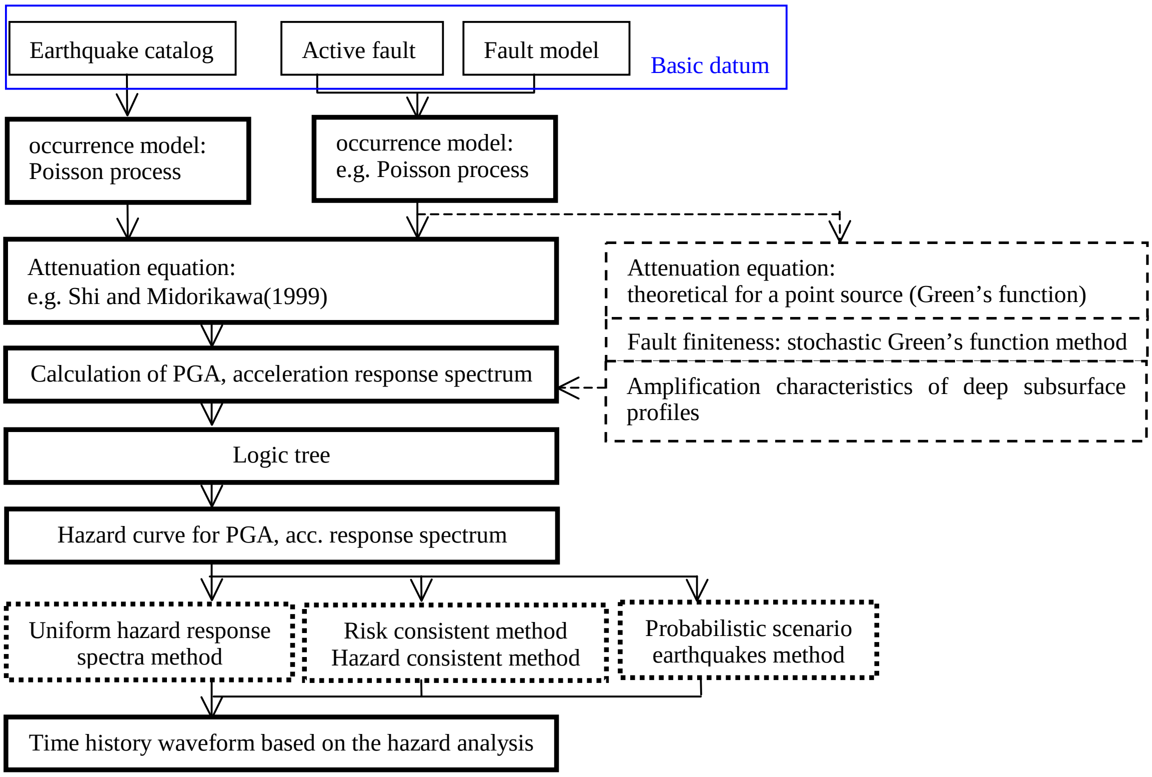
When using active fault data, the engineers often express the sizes of the earthquakes generated by active faults by a maximum magnitude model (maximum moment model) specific to each active fault. In such cases, the sizes and the occurrence rates of earthquakes are generally calculated from topographical and geological data such as the lengths and the average displacement velocities of active faults.

2.1.3. Assessment of the Attenuations of Seismic Ground Motions

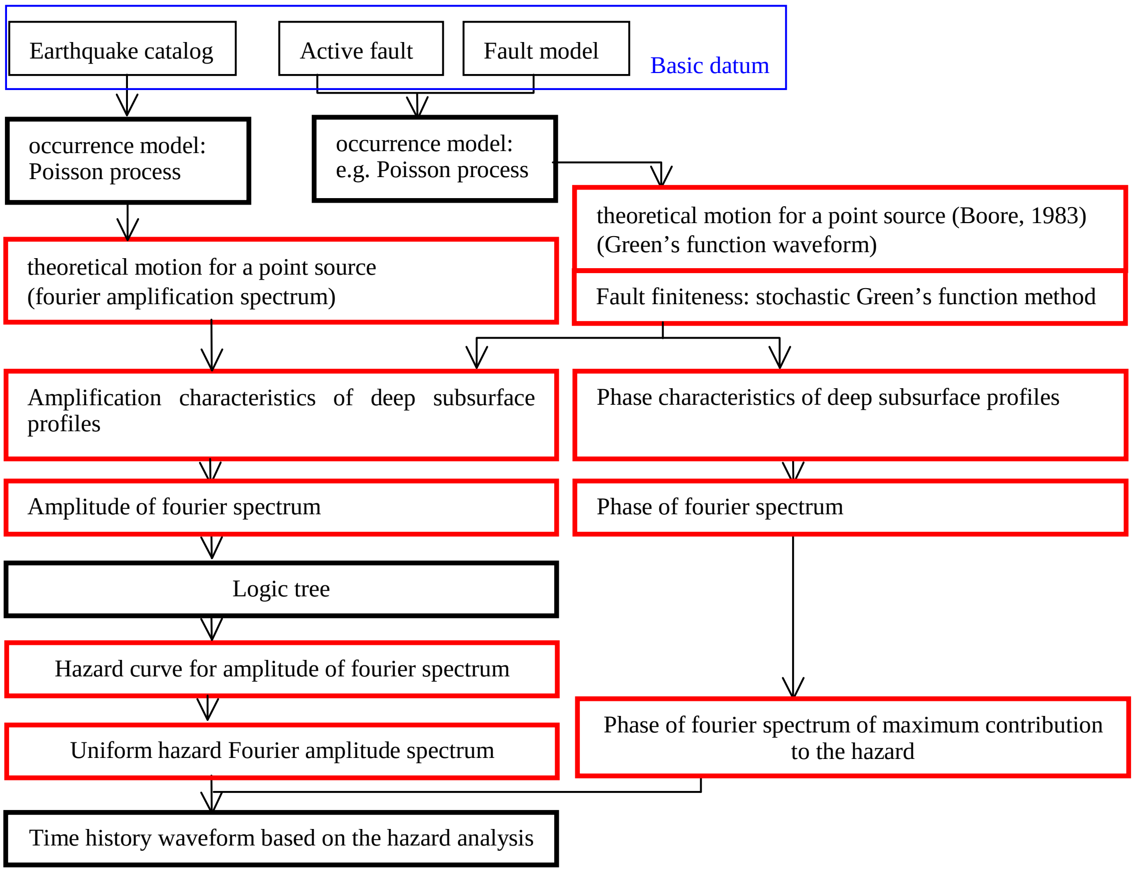
The attenuation equations for seismic ground motion intensities (e.g., maximum accelerations and response spectra) are often used for assessing seismic ground motions. In the attenuation equations, the average or median values and the dispersions of seismic ground motion intensities are given as functions of magnitudes and distances. In recent years, a stochastic Green’s function method is occasionally used for assessing seismic ground motion intensities, taking account of fault finiteness.

2.1.4. Calculation of Annual Probability of Exceedance

Using the results of the assessments described in Subsections 2.1.1 to 2.1.2, the annual occurrence rates calculated for each seismic ground motion intensity at each earthquake province and each active fault are summed up for all earthquake provinces and active faults. Then the annual frequency of experiencing seismic ground motions with intensities equal to or larger than a certain value (hereafter



(a) Conventional method



(b) Proposed method

Figure 1. Flowchart of seismic hazard analysis for probabilistic time history waveform

called annual occurrence rate) at the assessment site is calculated. Thus, the annual probability of exceedance is obtained as a function of ground motions intensities, which is called the ‘hazard curve’.

Logic trees are used for evaluating the uncertainties of the results caused by the assumptions used during assessment and by the selection of models. The logic trees analyse the properly-set combinations of models and parameters to evaluate the reliabilities from the dispersions of analysed results.

2.2. Calculation of Time History Waveforms

Several approaches, such as those using uniform hazard (response) spectra, risk (hazard) consistent seismic ground motion, and probabilistic scenario earthquakes, have been proposed to derive time history waveforms from the results of seismic hazard analyses.

2.3. Major Problems of the Conventional Seismic Hazard Analysis

The conventional seismic hazard analysis described in Sections 2.1 and 2.2 has the following problems:

(i) The conventional seismic hazard analysis invariably uses maximum accelerations or acceleration response spectra as the representative values of seismic ground motions to obtain the time history waveforms of earthquakes. The calculation takes the following steps: 1.earthquake sizes, distances, 2.maximum accelerations, 3.the hazard curves of maximum accelerations, 4.the time history waveforms of scenario earthquakes, or: 1.earthquake sizes, distances, 2.acceleration response spectra, 3.the hazard curves of acceleration response spectra, 4.the time history waveforms of scenario earthquakes.
(ii) The conventional method generally uses attenuation equations to determine maximum accelerations or acceleration response spectra, and in some cases it does not take account of the physical factors influencing seismic ground motions such as seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles. Even if approaches capable of taking account of fault models are used to calculate time history waveforms, hazard analyses are made on the maximum accelerations or the acceleration response spectra. Hence the degrees of contribution of the influential factors described above are limited.
(iii) In the cases of using probabilistic scenario earthquakes, it is possible to assess the seismic ground motions of selected scenario earthquakes taking account of the seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles. It is, however, difficult to determine the seismic ground motions that satisfy the probability levels given simultaneously in multiple frequency ranges.

3. PROPOSED PROBABILISTIC SEISMIC HAZARD ANALYSIS (PROBABILISTIC METHOD FOR ESTIMATING DESIGN INPUT SEISMIC GROUND MOTIONS)

To resolve the problems described in Chapter 2, we propose a new seismic hazard analysis using Fourier amplitudes and group delay times. The proposed method does not use the representative values such as maximum accelerations and response spectra. Taking advantage of the linearity of operation among various characteristics described above, the method uses Fourier amplitude spectra and the group delay times representing phase characteristics to directly calculate the time history waveforms that satisfy uniform hazard Fourier amplitude spectra. It adopts a stochastic Green’s function method as a convenient tool to calculate time history waveforms taking account of the various characteristics described above. Figure 1(b) shows the overall flow of the proposed method. The red frames in Figure 1 indicate the processes where the proposed method is different from the conventional method. Major characteristics of the proposed method are described below in detail.

3.1. Handling of Seismic Source, Propagation Path, and the Ground Motion Amplification Characteristics of Deep Subsurface Profiles in the Proposed Method

3.1.1. Approach to Estimate Seismic Ground Motions at the Site of Interest Based on Active Faults and Fault Models

To estimate the seismic ground motions (Fourier amplitude spectra and their corresponding time history waveforms) at the site of interest based on active faults and fault models, we determine seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles using the following approach as shown in the conceptual diagram of Figure 2. In calculating the time history waveforms, we also take account of the effects of the various characteristics described above on phases.

(i) Using primarily a stochastic Green's function method, we estimate seismic ground motions at the site of interest to express seismic source characteristics and propagation path characteristics.
(ii) Ground motions on the seismic bedrock from a subfault are assumed to follow the ω^{-2} model and their Fourier amplitude and phase are evaluated based on the approach proposed by Boore(1983).
(iii) The medians of seismic source parameters are estimated based on the results of past studies on seismic sources or the "recipe" for strong ground motion estimation.
(iv) Using the results of the study of Yamada et al.(2004), asperites and rupture starting points are distributed randomly and uniformly on the fault planes. Logic trees are used to estimate the dispersions of the indices unable to be expressed by random dispersions.
(v) As for propagation path characteristics, we use the region-wise Q values that have been proposed in past studies.
(vi) The results of spectral inversion on the site of interest are used for calculating the amplification characteristics of deep subsurface profiles (between seismic bedrocks to engineering bedrocks). We also take account of the phase delays occurring in the subsurface profiles between seismic bedrocks and engineering bedrocks.

3.1.2. Approach to Estimate Seismic Ground Motions at the Site of Interest Using Earthquake Catalog Data

We regard the seismic ground motions occurring at the site of interest obtained from earthquake catalog data as background data (here, background means that "it cannot be related to specific active faults), and so we do not take fault finiteness into consideration. We therefore estimate Fourier amplitude spectra instead of time history waveforms. Seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles are estimated through the following procedure as shown in the conceptual diagram of Figure 3.

(i) Assuming that seismic activities are uniform over each earthquake province, we first distribute seismic sources over the earthquake province of interest. Based on a Gutenberg-Richter's relation and a relational expression between magnitudes and seismic moments, we then define the sizes of the earthquakes (using the seismic moment M_0).
(ii) Assuming the ω^{-2} spectral model, we calculate the Fourier amplitude spectra on the seismic bedrocks.
(iii) The region-wise Q values that have been proposed in past studies are used to indicate propagation path characteristics.
(iv) The results of spectral inversion on the site of interest are used for calculating the amplification characteristics of deep subsurface profiles (between seismic bedrocks and engineering bedrocks).

3.2. Uniform Hazard Fourier Amplitude Spectra and the Preparation of Corresponding Time History Waveforms

3.2.1. Preparation of Hazard Surfaces

The processes described in Sections 3.1 enable us to obtain Fourier amplitude spectra from earthquake catalog data with occurrence probabilities, and to obtain time history waveforms with occurrence probabilities from active fault models and fault models.

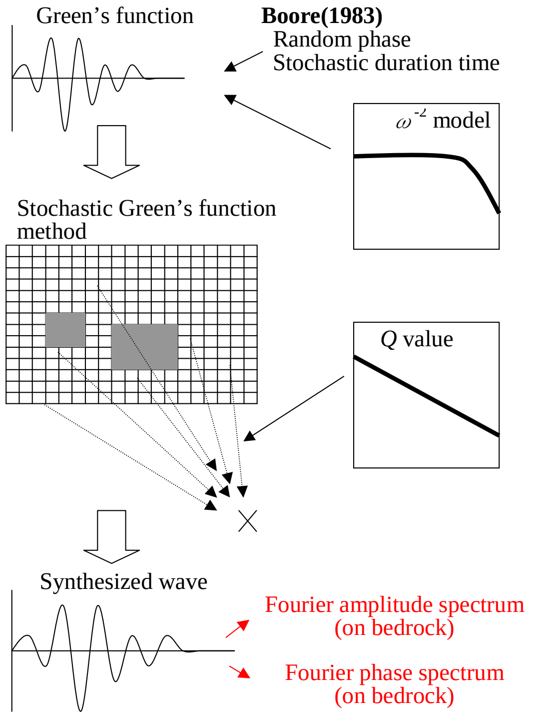


Figure 2. Estimation for active fault and fault model

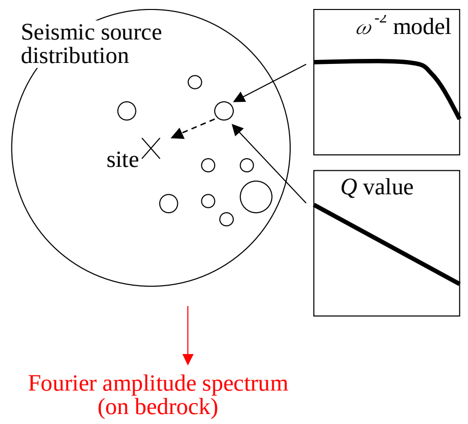


Figure 3. Estimation for earthquake catalog data

3.2.1. Preparation of Hazard Surfaces

The processes described in Sections 3.1 enable us to obtain Fourier amplitude spectra from earthquake catalog data with occurrence probabilities, and to obtain time history waveforms with occurrence probabilities from active fault models and fault models.

Using the Fourier amplitude spectra obtained from earthquake catalog data, we determine the relationships between the values of Fourier amplitude spectra and annual occurrence rates for each frequency. Performing a Fourier transform, we transform the time history waveforms obtained from active fault models and fault models into Fourier amplitude spectra and Fourier phase spectra. Using the transformed Fourier amplitude spectra, we derive the relationships between the values of Fourier amplitude spectra and annual occurrence rates for each frequency as in the cases of earthquake catalog data.

For each frequency and each value of Fourier amplitude, the annual occurrence rates are summed up for all scenario earthquakes. The result can be expressed as the 'hazard surfaces' as shown in Figure 4.

Assuming a certain hazard level (*i.e.*, annual probability of exceedance) for the hazard surfaces, we acquire uniform hazard Fourier amplitude spectra as shown in Figure 4.

3.2.2. Preparation of Time History Waveforms Corresponding to Uniform Hazard Fourier Amplitude Spectra

The determination of the time history waveforms corresponding to uniform hazard Fourier amplitudes requires phase information. Since there is no definite relationship between phases and hazard levels, we cannot easily obtain the Fourier phase spectra at a uniform hazard level. We therefore use the Fourier phase spectra obtained from the time history waveforms corresponding to each active fault model and each fault model to calculate Fourier phase spectra. Here we obtain fractional contribution from earthquake catalog data, active fault models, and fault models, adopting the Fourier phase spectra of the seismic sources having the highest fractional contribution with respect to the values of uniform Fourier amplitude spectra. If the earthquake catalog data has the highest fractional contribution, Fourier phase spectra assuming a point source is considered.

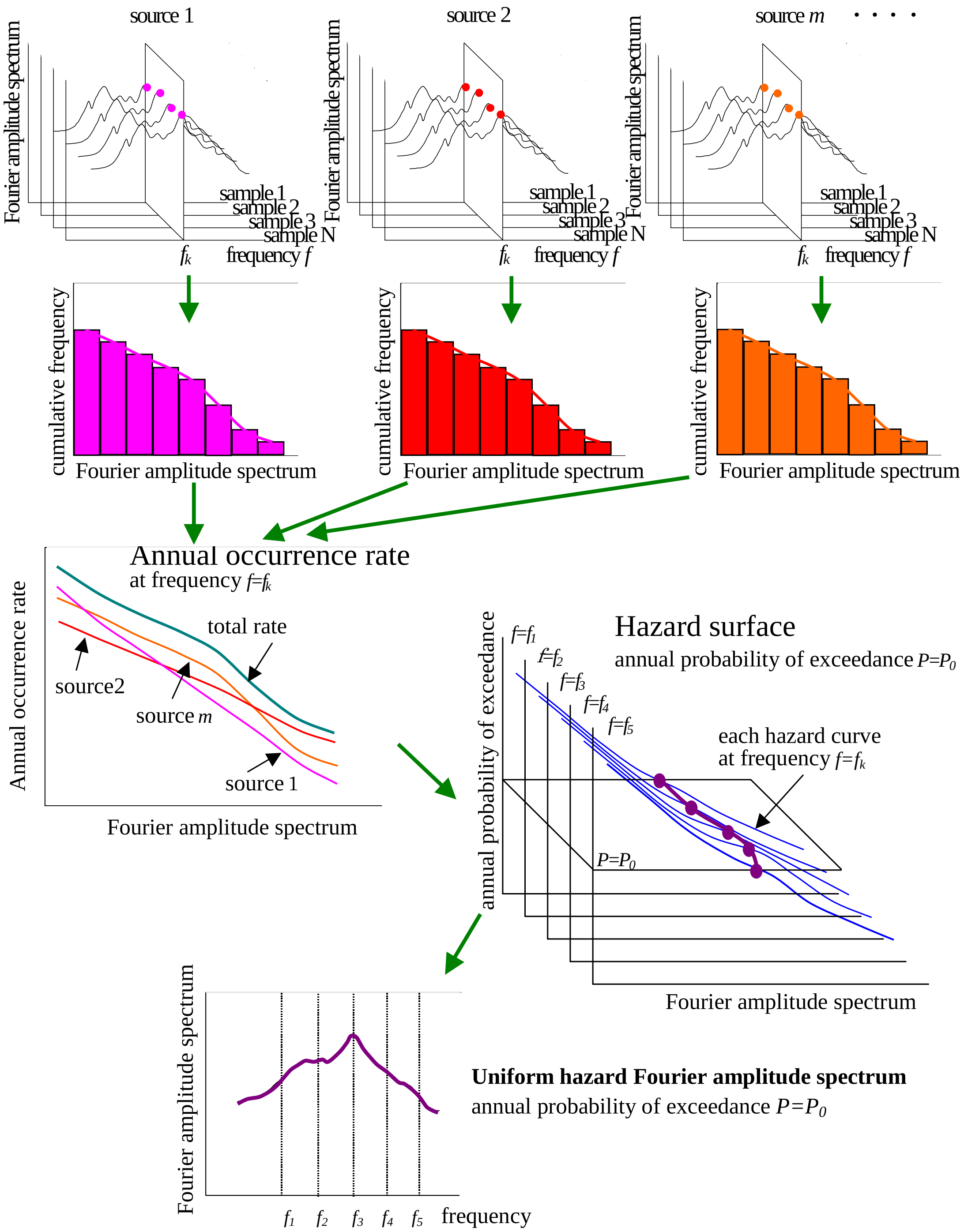


Figure 4. Procedure for calculating uniform hazard Fourier amplitude spectrum

Applying an inverse Fourier transform to these uniform hazard Fourier spectra and to the Fourier phase spectra selected by using the fractional contribution, we acquire probabilistic design input seismic ground motions (time history waveforms).

4. APPLICATIONS TO TOHOKU REGION

We applied the proposed method to Sendai-Shiogama port (Sendai district) and discussed the effect of the 2011 off the Pacific Coast of Tohoku earthquake (hereafter Tohoku earthquake) on the probabilistic ground motions.

4.1. Source model for Tohoku earthquake

We set source model for Tohoku earthquake according to Nozu(2012, this issue). Figure 5 shows the source area, the epicenter (black star in Figure 5) and the subevents (SAs) (blue squares in Figure 5). The parameters of the subevents are shown in Table 1.

4.2. Application of the proposed method to the Sendai-Shiogama port (Sendai district)

The proposed probabilistic ground motions were evaluated for two conditions: with and without Tohoku earthquake. In the probabilistic process, the dispersions on the position and the seismic moment of each SA and the site amplification factor were considered. Each SA was randomly located in the landside of the source area (gray squares in Figure 5) from where strong motions are mainly generated. The average interval of the source activity was determined as 1000 years, taking the Jogan earthquake in 869 A.D. into consideration as the latest 2011-type recurrence event.

The time histories of predicted probabilistic ground motions at Sendai-Shiogama port (Sendai district) are shown in Figure 6. In Figure 6(a), Tohoku earthquake is not considered. In Figure 6(b), Tohoku earthquake is considered. In the range of comparatively large annual probability of exceedance (1/75), maximum amplitude and the envelope of waveforms are not significantly different. On the other hand, in the range of small annual probability of exceedance (1/1000), maximum amplitude with Tohoku earthquake is one and a half times ~~of~~ that without Tohoku earthquake. Duration and envelope of waveform are also significantly different because of the influence of Tohoku earthquake. Figure 7 shows the fractional contribution of each source in the probabilistic ground motions. Tohoku earthquake has small fractional contribution within the range of large annual probability of exceedance, but has large fractional contribution at 1/1000 probability of exceedance that corresponds to the assumed average interval. Figure 8 shows the acceleration response spectra of the observation record of Tohoku earthquake and of the predicted probabilistic motion with 1/1000 annual probability of exceedance for 90% confidence level. The predicted spectrum is in good agreement with the observed spectra.

5. CONCLUSION

In this paper we proposed a new framework for probabilistic seismic hazard analyses focusing on Fourier amplitudes and group delay times as an approach to directly calculate the time history waveforms of the seismic ground motions corresponding to arbitrary annual probability of exceedance, taking account of seismic source characteristics, propagation path characteristics, and the ground motion amplification characteristics of deep subsurface profiles. We also explained some results of applying the proposed seismic hazard analyses to earthquakes that have occurred in the Tohoku region.

One of the advantage of the proposed method is that the physical factors influencing seismic ground motions, such as seismic source characteristics, propagation path characteristics, and the seismic amplification characteristics of deep subsurface profiles, in the process of seismic hazard analyses. Applicability of the proposed method to the site in eastern Japan region was shown.

AKCNOWLEDGEMENT
We sincerely thank the members of the National Research Institute for Earth Science and Disaster Prevention for providing the observation records of K-NET and KiK-net.

Table 1. Source parameter of the 2011 Tohoku earthquake

	rupture time (hh:mm:ss)	length (km)	width (km)	seismic moment (Nm)	rise time (s)
SA1_1	14:46:43.5	3.0	2.0	8.00E+18	0.17
SA1_2	14:46:46.9	4.0	3.0	8.00E+18	0.25
SA1_3	14:47:33.4	4.0	2.0	4.00E+18	0.17
SA2	14:47:26.3	3.5	3.0	2.10E+19	0.25
SA3_1	14:47:57.1	3.0	4.0	3.00E+18	0.33
SA3_2	14:48:04.4	3.0	4.0	3.00E+18	0.33
SA3_3	14:48:15.0	6.0	2.0	5.00E+18	0.17
SA4	14:48:25.8	8.0	3.0	9.00E+18	0.25
SA5	14:48:30.9	7.0	7.0	2.00E+19	0.58

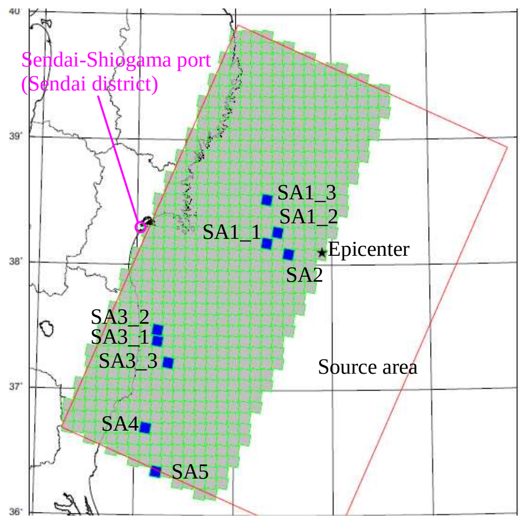
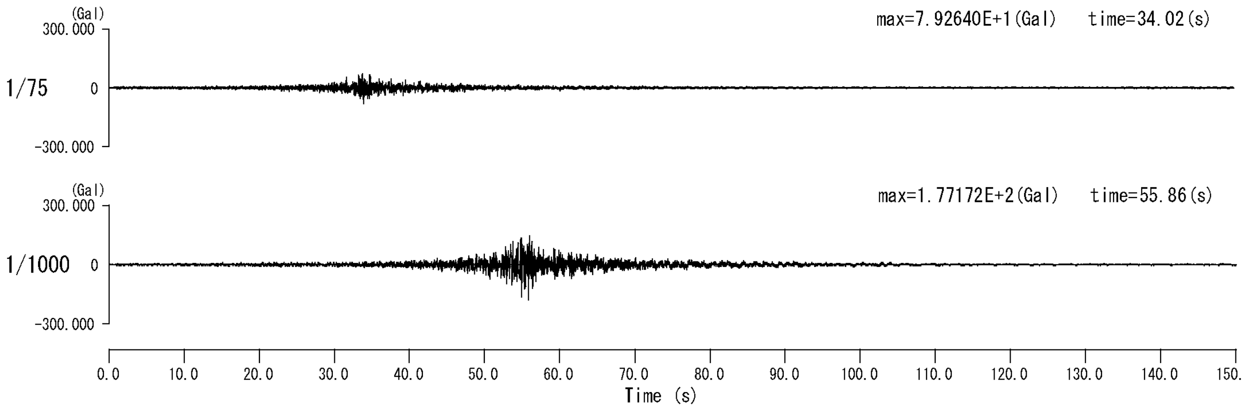
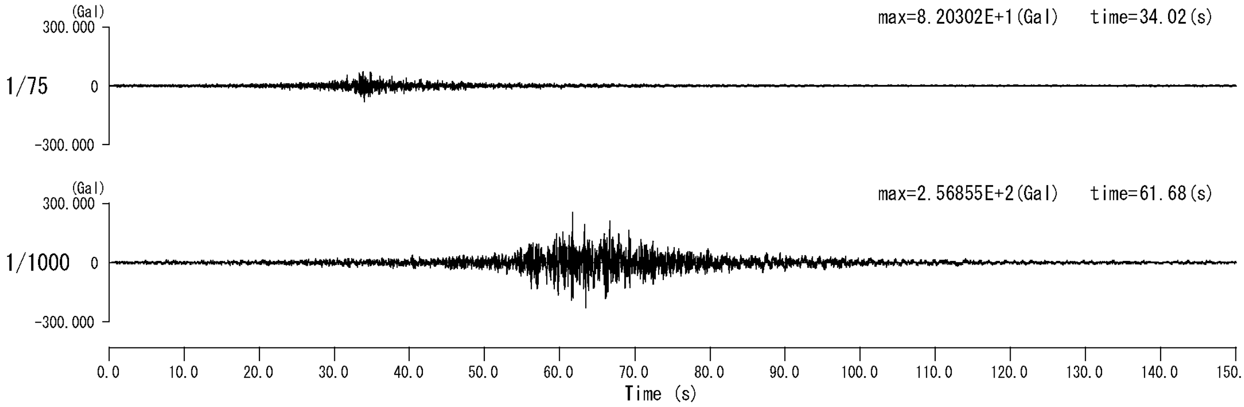


Figure 5. Source model of the Tohoku earthquake



(a) without consideration of the Tohoku earthquake



(b) with consideration of the Tohoku earthquake

Figure 6. Predicted time history waveforms at Sendai-shiogama port with 1/75, 1/1000 annual probability of exceedance for 50% confidence level, with and without Tohoku earthquake

REFERENCES

Abrahamson, N. A. (2000). State of the Practice of Seismic Hazard Evaluation. Proceedings of International conference on geotechnical and geological engineering (GeoEng 2000), Vol.1, 659-685.

Boore, D.M. (1983). Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bulletin of the Seismological Society of America. Vol.73, 1865-1894.

Dan, K., T. Sato and K. Irikura. (2002). Characterizing Source Model for Strong Motion Prediction based on Asperity Model. Proc. of 11th Japan Earthquake Engineering Symposium. CD-ROM.

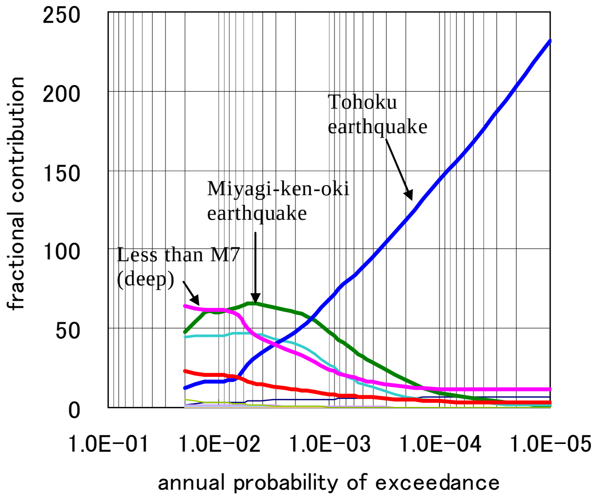


Figure 7. Fractional contribution of each source at Sendai-shiogama port

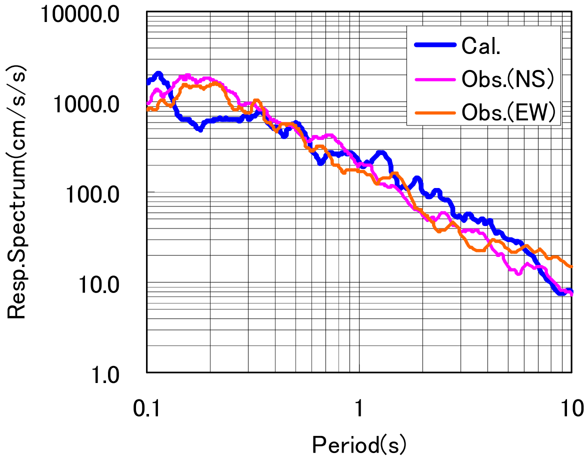


Figure 8. Acceleration response spectra by the observed and predicted (1/1000 annual probability of exceedance for 90% confidence level) waveforms of the Tohoku earthquake at Sendai-shiogama port

Irikura, K. and H. Miyake. (2001). Prediction of Strong Ground Motions for Scenario Earthquakes. Journal of Geography. Vol.110: No.6, 894-875.

Iwata, T. and K. Irikura. (1986). Separation of Source, Propagation and Site Effects from Observed S-Waves. Zisin, 2nd series. Vol.39: No.4, 579-593.

Japan Atomic Energy Research Institue. (1999). Summary Report of Seismic PSA of BWR Model Plant. JAERI-Research. 99-035.

Japan Society of Civil Engineers Special Task Committee of Earthquake Resistance of Civil Engineering Structures. Proposal on Earthquake Resistance for Civil Engineering Structures. http://www.jsce.or.jp/committee/earth/propo3.html.

Kamae, K., K. Irikura, and Y. Fukuchi. (1991). Prediction of Strong Ground Motion based on Scaling Law of Earthquake. Journal of Struct. Constr. Engng, AIJ. No.430, 1-9.

Kameda, H. and N. Nojima. (1987). Simulation of Risk-Consistent Earthquake Ground Motions. Annuals of Disas. Prev. Res. Inst., Kyoto Univ. No.30: B-2, 107-119.

Kameda, H., Y. Ishikawa, T. Okumura and M. Nakajima. (1997). Probabilistic Scenario Earthquakes. Journal of Structural Mechanics and Earthquake Engineering. No.557: I -41, 75-87.

Kowada, A., M. Tai, Y. Iwasaki and K. Irikura. (1998). Evaluation of Horizontal and Vertical Strong Ground Motions using Empirical Site-Specific Amplification and Phase Characteristics. Journal of Struct. Constr. Engng, AIJ. No.514, 97-104.

McGuire, R.K. (1976). FORTRAN Computer Program for Seismic Risk Analysis. United States Department of the Interior Geological Survey, Open-File Report. 76-67.

Nagao, T and M. Yamada. (2002). Application of Stochastically Simulated Green's Function Method for Seismic Hazard Analysis. Proc. of 11th Japan Earthquake Engineering Symposium. CD-ROM.

Nagao T., M. Yamada, and A. Nozu. (2005). Probabilistic seismic hazard analysis with focus on fourier amplitude and group delay time. Journal of Japan Society of Civil Engineers. No.801: I -73, 141-158.

Nakajima, M. and K.Hirata. (2002). Current Status and Problems of Probabilistic Seismic Hazard Analysis. Abiko Research Laboratory Rep. U01057, 1-24.

Nozu A. (2012). Constructing a Source Model Composed of Super Asperities for the 2011 Off the Pacific Coast of Tohoku Earthquake, Proceedings of the 15th World Conference on Earthquake Engineering (this issue).

Satoh, T. and Y. Tatsumi. (2002). Source, Path, and Site Effects for Crustal and Subduction Earthquakes Inferred from Strong Motion Records in Japan. Journal of Struct. Constr. Engng, AIJ. No.556, 15-24.

Sato, T., Y. Murono and A. Nishimura. (1999). Modeling of Phase Characteristics of Strong Earthquake Motion. Journal of Structural Mechanics and Earthquake Engineering. No.612: I-46, 201-213.

Sawada, S., H. Morikawa, K. Toki and K. Yokoyama. (1998). Identification of Path and Local Site Effects on Phase Spectrum of Seismic Motion. Proc. of 10th Japan Earthquake Engineering Symposium. 915-920.

Sokolov, V. Y. (2000). Hazard-Consistent Ground Motions: Generation on the Basis of Uniform Hazard Fourier Spectra. Bulletin of the Seismological Society of America. Vol.90, 1010-1027.

Yamada, M., H. Fujiwara and S. Senna. (2004). Statistical Analysis of Predicted Ground Motions for Scenario Earthquakes. Abstracts, 2004 Japan Earth and Planetary Science Joint Meeting.