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OUTLINE OF STRONG-MOTION EVALUATION IN SEISMIC HAZARD MAPPING PROJECT OF JAPAN

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SUMMARY

The National Research Institute for Earth Science and Disaster Prevention (NIED) has carried on the special research project 'National Seismic Hazard Mapping Project of Japan' to support the preparation of the National Seismic Hazard Maps made by the Headquarters for Earthquake Research Promotion. The seismic hazard maps consist of two kinds of hazard maps. One kind of hazard map is a probabilistic seismic hazard map that shows information predicting possibility that a certain area is attacked by a strong ground motion in a certain term by means of probability. The other kind of hazard map is a scenario earthquake map with a specified seismic fault. As the first step in preparations for producing the seismic hazard maps, which are scheduled to be completed by the end of fiscal year 2004, preliminary versions of the probabilistic seismic hazard maps for restricted regions and seismic hazard maps for several scenario earthquakes have been made. In this article, the outline of methodologies to evaluate strong-motion distributions both for the probabilistic seismic hazard maps and for the scenario seismic hazard maps is presented.

INTRODUCTION

The Great Hanshin-Awaji Earthquake Disaster on January 17, 1995 killed more than 6,400 people. Following on the lessons learned from this disaster, Earthquake Disaster Management Special Act was enacted in July 1995 to promote a comprehensive national policy on earthquake disaster prevention. In accordance with this act, the Headquarters for Earthquake Research Promotion was established. In April 1999, Headquarters for Earthquake Research Promotion fixed 'On Promotion of Earthquake Research – Comprehensive and Fundamental Measures for Promotion of Observation, Measurement and Research on Earthquakes—'. In this article, the Headquarters for Earthquake Research Promotion concluded that preparation of 'National Seismic Hazard Maps of Japan' should be promoted as a major subject of earthquake research. The National Research Institute for Earth Science and Disaster Prevention (NIED) started the special research project 'National Seismic Hazard Mapping Project of Japan' to support the preparation of seismic hazard maps made by the Headquarters for Earthquake Research Promotion in April 2001. The National Seismic Hazard Maps of Japan consists of two kinds of hazard maps. One kind of hazard map is a probabilistic seismic hazard map that shows the relation between seismic intensity value and its probability of exceedance within certain time period. The other kind of hazard map is a seismic hazard map with a specified seismic source fault. This type of hazard map is sometimes called

scenario earthquake map. As the first step in preparations for producing the seismic hazard maps, which are scheduled to be completed by the end of fiscal year 2004, preliminary versions of probabilistic seismic hazard maps for the region centering North Japan and scenario seismic maps for several earthquakes, e.g. earthquakes in Itoigawa Shizuoka tectonic line fault zones, Miyagi-ken-oki earthquakes, have been prepared. We present the outline of methodologies to evaluate spatial strong-motion distributions both for the probabilistic seismic hazard maps and for the scenario seismic hazard maps.

STRONG-MOTION EVALUATION IN PROBABILISTIC SEISMIC HAZARD MAPS

In the probabilistic seismic hazard maps, probability or annual rate of earthquake occurrence and strong-motion levels for all possible earthquakes are evaluated. The procedure of the seismic hazard evaluation used in the Seismic Hazard Mapping Project is the followings.

(1) Following the classification of earthquakes (Table 1) by the earthquake research committee of Japan, we model the seismic activities in Japan.
(2) The occurrence probability is evaluated for each earthquake.
(3) Probabilistic evaluation model of strong-motion level is selected for each earthquake.
(4) Probability that some intensity measure of strong-motion will exceed certain level during a specified time period is evaluated for each earthquake.
(5) Considering the contribution from all possible earthquakes, we evaluate the probability that the intensity measure of strong-motion will be exceeded during a specified time period.

Table 1
Seismic activity model for the probabilistic hazard maps

Classification of earthquakes by the earthquake research committee	Location of earthquake	Magnitude of earthquake	Earthquake occurrence model	Occurrence probability or rate
Characteristic earthquakes in 98 major active fault zones	Specified fault	Characteristic earthquake	Renewal or Poisson	Long-term evaluation*
Characteristic earthquakes at the oceanic plate boundaries (subduction earthquakes)	Specified fault	Characteristic earthquake	Renewal or Poisson	Long-term evaluation*
Characteristic earthquakes in active fault zones except for 98 major active fault zones	Specified fault	Characteristic earthquake	Poisson	Based on active fault data
Background earthquakes at the oceanic plate boundaries	Distributed	Gutenberg - Richter	Poisson	Based on earthquake catalog
Background earthquakes in the Pacific plate and the Philippine sea plate	Distributed	Gutenberg - Richter	Poisson	Based on earthquake catalog
Background earthquake in the upper crust	Distributed	Gutenberg- Richter	Poisson	Based on earthquake catalog
Earthquakes in active fault zones except for characteristic earthquakes (not considered in this study)		–		
Other background earthquakes in particular region	Distributed	Gutenberg - Richter	Poisson	Based on earthquake catalog

* Long-term earthquake occurrence probability evaluation by earthquake research committee of Japan.

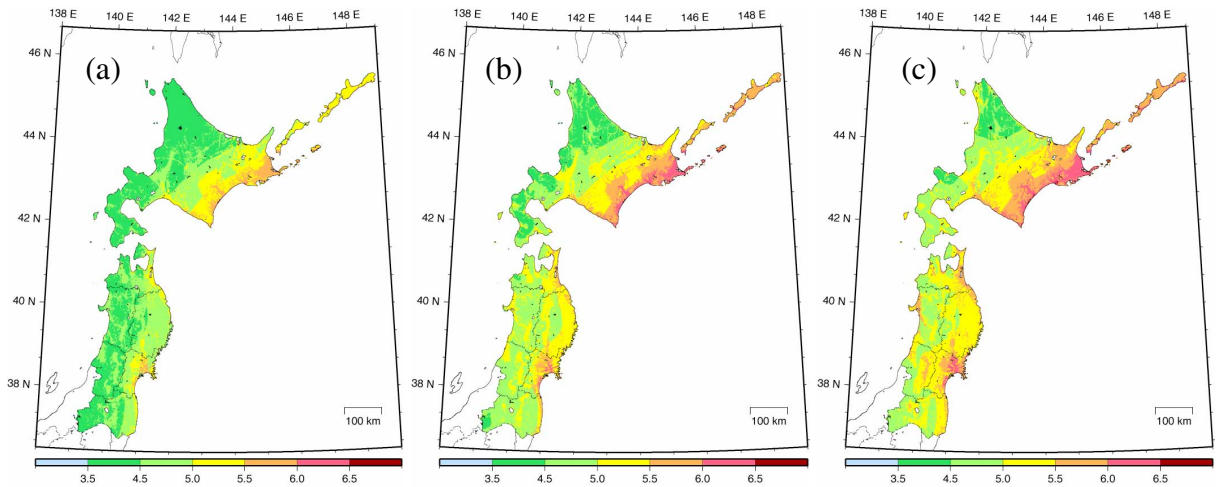

Fig.1. Examples of probabilistic seismic hazard maps for the North Japan. The maps (a), (b), (c) show the JMA seismic intensity of 39%, 10% and 5% in 50 year probability of exceedance, respectively.

In the procedure (3), we use empirical attenuation relations (Si [1]) for intensity measures of strong-motion. It is difficult to adopt simulation methods based on source modeling such as the hybrid method because the simulation methods need too much computation to evaluate spatial distributions of strong-motion for all possible earthquakes.

In the probabilistic seismic hazard maps, peak ground velocity (PGV) on the engineering bedrock (Vs=400m/s) and PGV on the ground surface are evaluated for the sites with approximately 1km spacing. The JMA seismic intensities on the ground surface are also evaluated by using an empirical formula (Midorikawa [2]).

Examples of the probabilistic seismic hazard maps ([3], [4], [5], [6]) for the North Japan are shown in Fig 1. These maps show the JMA seismic intensity corresponding to the probability of exceedance of 39%, 10% and 5% in 50 years starting from January, 2003, respectively.

It is pointed out that the seismic hazard is relatively high in the eastern part of the depicted area due to the large earthquakes with high probability of occurrence in the subduction zone of the Pacific plate. The effect of the surface ground condition to the seismic hazard is also clearly seen in the figures; the area covered with soft soil such as planes and basins has relatively high seismic hazard.

After these maps are evaluated, several major earthquakes including 2003 Tokachi-oki earthquake hit the northern part of Japan. During these earthquakes, JMA seismic intensity 6- was observed at several sites. Since it has been confirmed that most of these sites were located in the area of high seismic hazard, the efficiency of the use of the probabilistic seismic hazard maps is recognized.

STRONG-MOTION EVALUATION FOR SCENARIO EARTHQUAKES

In the National Seismic Hazard Mapping Project, not only the probabilistic seismic hazard maps but also hazard maps for earthquakes in specified seismic source fault (scenario earthquake maps) are prepared for some earthquakes whose probabilities of occurrence are estimated in high level. Because of the limitation of computational capacity and information on modeling, it is difficult to evaluate strong-motion by using the simulation methods in the probabilistic seismic hazard maps. In the scenario earthquake maps, however, we adopt the simulation method based on the source modeling. Using the simulation method, it is possible to evaluate waveforms on the engineering bedrock as well as peak ground acceleration and peak ground velocity. The mesh size of scenario earthquake maps is about 1km. The intensity measures of strong-motion in the scenario earthquake maps are summarized in Table 2. Examples of the scenario earthquake maps are shown in Fig.2.

Table 2
The intensity measures of strong-motion in the scenario earthquake maps.

	Scenario earthquake maps on the engineering bedrock	Scenario earthquake maps on the ground surface
Mesh size	1 km^2	1 km^2
Peak ground acceleration (PGA)	○	×
Peak ground velocity (PGV)	○	○
Spectral acceleration (SA)	△	×
JMA seismic intensity	×	○
Time history of waveform	○	×

The hybrid method is adopted as the simulation method for strong-motion evaluation. The hybrid method aims to evaluate strong-motions in a broadband frequency range and is a combination of a deterministic approach using numerical simulation methods, such as the finite difference method (FDM) or the finite element method (FEM), for low frequency range and a stochastic approach using the empirical or stochastic Green's function method for high frequency range. A lot of information on source characterization and modeling of underground structure is required for the hybrid method. The standardization of the setting parameters for the hybrid method is studied in the National Seismic Hazard Mapping Project. In the followings, we summarized the technical details on the hybrid method based on the 'Recipe for strong-motion evaluation of earthquakes in active faults [7]' and 'Recipe for strong-motion evaluation of earthquakes in plate boundaries [8]', which are published by the earthquake research committee of Japan.

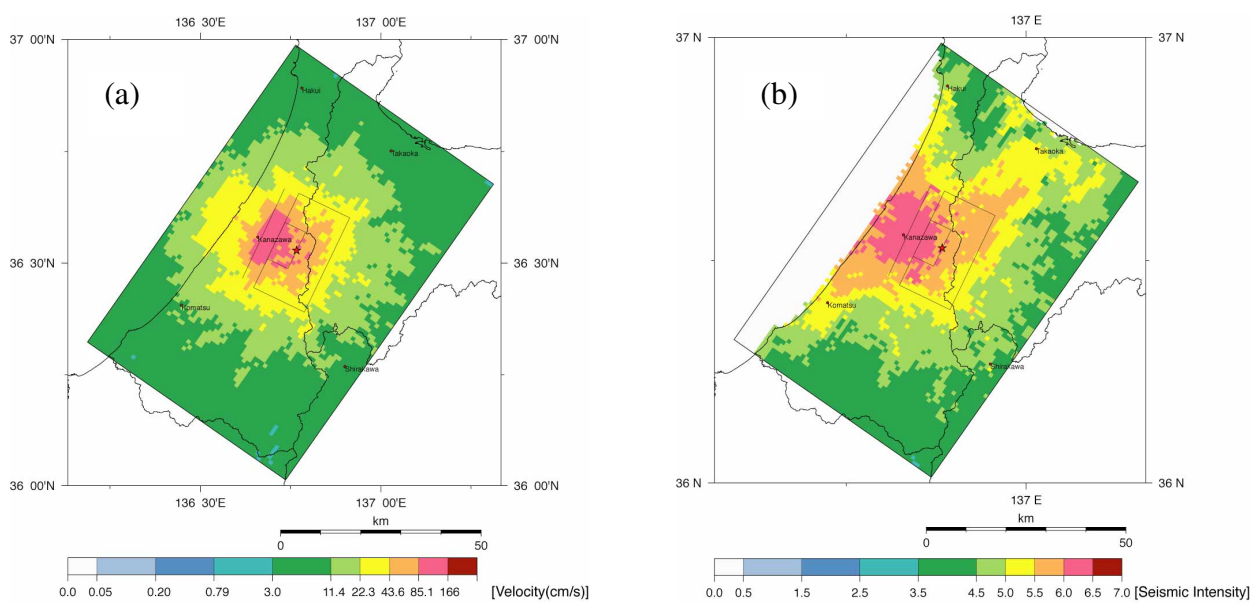

Fig.2. Distribution of peak ground velocity on the engineering bedrock (Vs=700m/s) for a scenario earthquake in Morimoto-Togashi fault zone is shown in (a). Distribution of JMA seismic intensity on the ground surface for the same earthquake of (a) is shown in (b).

Setting parameters for characterized source model

Characterized source models are composed of asperities and a background slip area surrounding the asperities (Fig.3). Source parameters required to evaluate strong-motions by using the characterized source model are classified into three parts. The first part is the set of outer parameters that show the magnitude and the fault shape of the earthquake. The second part is the set of the parameters that describe the degree of fault heterogeneity. The third part is the set of the parameters to define the characteristics of the rupture propagation.

Outer parameters for characterized source model

Outer parameters for characterized source model are the location of the earthquake, the size of rupture area, the depth, the magnitude or the seismic moment, and the average slip on the fault.

In the National Seismic Hazard Maps, the parameters for the location of the earthquake, the size of rupture area and the depth are given by the results of the long-term evaluation of earthquake activities by the earthquake research committee of Japan.

For the earthquakes which occur in active fault zones, the seismic moment M_0(dyne・cm) is given by the following relation ([7], Somerville [9], Wells [10], Irikura [11]),

$$S = \begin{cases} 2.23 \cdot 10^{-15} \cdot M_0^{2/3}, & M_0 \le 4.7 \cdot 10^{25} \\ 4.24 \cdot 10^{-11} \cdot M_0^{1/2}, & 4.7 \cdot 10^{25} < M_0 \le 1.0 \cdot 10^{28} \end{cases} \qquad (1)$$

where S is the rupture area estimated by the earthquake research committee.

For the earthquakes in the plate boundaries, considering the characteristics for each earthquake using the seismic data set, we determine the seismic moment individually.

Inner parameters for characterized source model

Inner parameters for characterized source model are the locations of the asperities, the number of asperities, the areas of the asperities, average slips and effective stresses in the asperities, average slips and effective stresses in the background slip area, f_{max} and the slip velocity time function. For the earthquakes in active fault zons, we determine the locations of asperities considering the results of the investigation of active faults, such as trench surveys, and put the asperities just under the positions where the large dislocations are observed. The number of asperities is usually one or two for one segment of an active fault. For earthquakes in the plate boundaries, considering the characteristics for each earthquake using the seismic data set and results from inversion of rupture process for the post earthquakes, we determine the locations and the number of the asperities. In this procedure, we often assume that the locations of the asperities are invariants.

Using the empirical relation between the seismic moments and high frequency level in the source spectrum of acceleration A(dyne・cm/s^2), the area of asperities is given by the following relations,

$$\begin{aligned} S_a &= \pi r^2 \\ r &= \frac{7\pi}{4} \cdot \frac{M_0}{A \cdot R} \cdot \beta^2 \\ A &= 2.46 \cdot 10^{17} \cdot M_0^{1/3} \end{aligned} \qquad (2)$$

where R is the radius of the circular crack whose area is the same as the fault area and β is the shear wave velocity in the fault region

The ratio of the average slip in asperities D_a and the average slip in background slip area D_b is assumed 2 to 1. The average stress drop in the asperities are given by

$$\Delta\sigma_a = \frac{7}{16} \cdot \frac{M_0}{r^2 R} \qquad (3)$$

We assume that the effective stress in the asperities σ_a is equivalent to the average stress drop. The effective stress in the background domain is given by

$$\sigma_b = \frac{(D_b / W_b)}{(D_a / W_a)} \cdot \sigma_a \qquad (4)$$

where W_a and W_b show the width of asperity and background slip area, respectively.

We determine the cut off frequency f_{max} individually for each earthquake considering the regional characteristics of the earthquakes. For the slip velocity time function, we adopt the function obtained from the consideration in the basis of the rupture simulation using a dynamic source model (Nakamura [12]).

Other parameters for characterized source model

Other parameters for characterized source model are the starting point of the rupture, the pattern of the rupture propagation and the rupture velocities.

For the earthquakes in active fault zones, we determine the starting point of the rupture using the branch patterns of the faults if we can use the information on that. The starting point is put out of asperities. If we have no information on the starting point, we put the starting point at the bottom of an asperity. For the earthquakes in the plate boundaries, considering the characteristics for each earthquake using the seismic data set and results of inversion of rupture process of the post earthquakes if we can use, we determine the starting point. We assume several cases of the characteristic source model when we do not have information enough because the spatial distribution of strong-motion is strongly depend on the locations of asperities and the starting point of the rupture. When we have no information on the rupture pattern, we assume that the rupture propagates like a concentric circle at a constant velocity from the starting point. The rupture velocity is given by Geller [13]

$$V_r = 0.72\beta . \qquad (5)$$

Modeling of underground structure

We need seismic velocity and attenuation structure models to evaluate strong-motions. In modeling of underground structure (Fig.4), we consider the deep underground structure from the crust and plates up to seismic bedrock (Vs=3km/s), the structure of sediments from the seismic bedrock up to engineering bedrock (Vs=400m/s～700m/s), and the structure of surface soils from the engineering bedrock up to the ground surface.

Deep underground structure

The deep underground structure is the structure from the crust and plates up to seismic bedrock (Vs=3km/s). Using velocity and attenuation structure models obtained by the seismic tomography or geophysical explorations, we model the deep underground structure. It is required that the modeling deep underground structure down to the Moho discontinuity for earthquakes in active fault zones and the modeling of structure of plate boundaries for subduction earthquakes.

Structure of sediments

The structure of sediments from the seismic bedrock up to engineering bedrock (Vs=400m/s～700m/s) strongly affect the low-frequency strong-motions and is important factor for the evaluation of low-frequency strong-motions. In the modeling of the structure of sediments, we use profiles of deep boreholes, data from the reflection and refraction surveys, surveys using the microtremors, and data from the gravity surveys. We need to use an optimized modeling technique for available data sets in a target area because quantity and quality of information on underground structure are not uniform in all areas. In the modeling of underground structure for the strong-motion evaluations, seismic velocity structures are most important parameters. It is expected that the accuracy of the modeling is proportional to the quantity and the quality of data. In an ideal case we can use all data to be required, we make the three dimensional structure model using profiles of deep boreholes for accurate structure at some points, refraction data for boundary shapes in large sedimentary basins, reflection data to determine the boundary shapes of basin edges, and data from microtremor surveys and gravity surveys and geological information for spatial

interpolation. Furthermore, comparing the results of strong-motion evaluation using the above structure model to recorded seismograms, we verify the structure model and modify the model if it is necessary. Actually, however, it is difficult to obtain sufficient data required in the above ideal procedure for three-dimensional modeling of velocity structures in many cases. In such a case, available information distributed spatially is only the data from gravity survey and geological structure information. Using these data, we estimate velocity structures indirectly. Uncertainty in the velocity structure modeling is increase if we use only gravity data because the gravity data represent the density structure. Therefore we also use the information on geological structures to reduce the uncertainty.

Structure of surface soils

In the modeling of the structure of surface soils from the engineering bedrock up to the ground surface, profiles of boreholes and data of surface geology are basic information. The surface soil structures are locally very heterogeneous and large amount of data is required to model accurately the surface soil structure for a large area. In the case that strong-motion evaluation for large area is required, we adopt a rough estimation method to obtain amplifications of surface soils. The rough estimation method (Matsuoka [14], Fujimoto [15]) is based on the Digital Nation Land Information on geological data and geomorphological data. The mesh size of these data is about 1km. The average shear wave velocity for surface structure down to 30m is estimated by using the empirical relation between microgeographical data and the averaged shear wave velocity. Next the amplification factors for PGV are obtained from the empirical relation between the averaged shear wave velocity and PGV.

In the case that we can use sufficient information on surface soil structures, in stead of the rough method, we adopt a more accurate method in which we model the surface soil velocity structure for each mesh using many boring profiles and geological data.

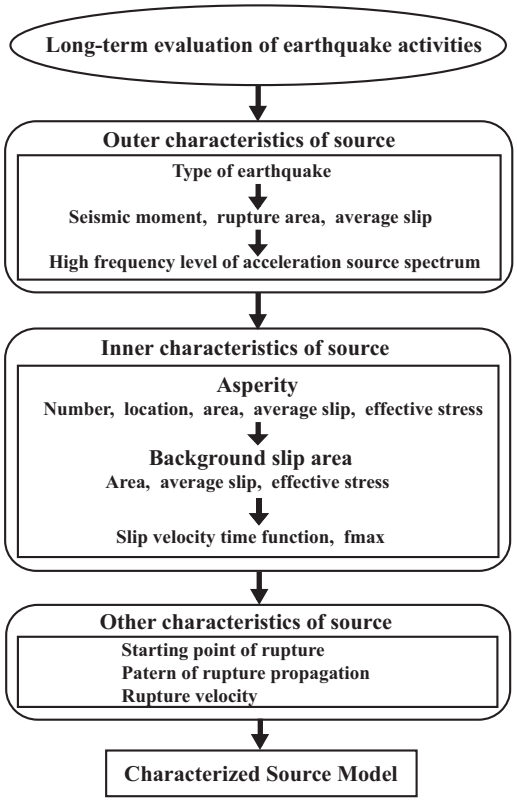

Fig.3. Flowchart of source modeling.

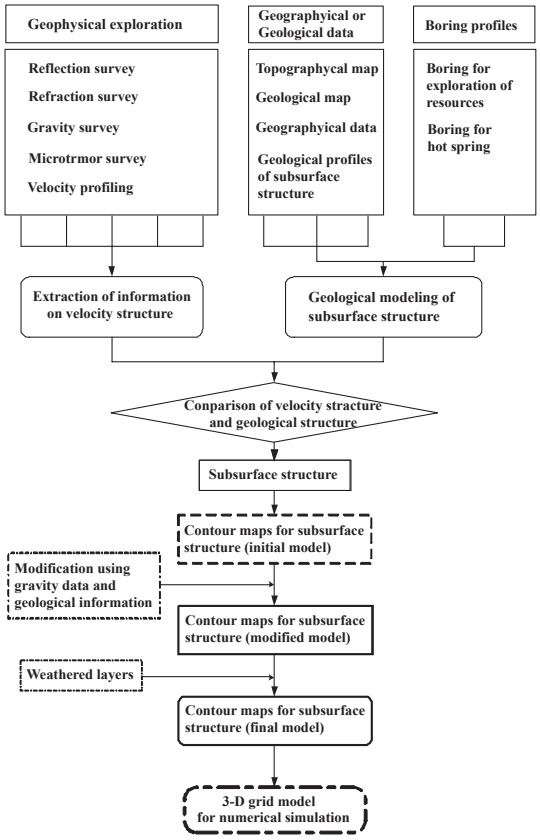

Fig.4. Flowchart of structure modeling.

Broadband strong-motion simulation using the hybrid method

Characteristics of low frequency strong-motions can be explained using deterministic simulations based on physical models given by the elastodynamic theory. On the other hand, it is difficult to evaluate characteristics of high frequency strong-motions using the deterministic approaches because the uncertainty in the setting parameters for the simulations become too large due to the lack of information on both source modeling and structure modeling. Instead of the deterministic approach, we need to adopt a stochastic approach to evaluate high frequency strong-motions. Using broadband strong-motion simulations, we aim to evaluate strong-motions in frequency range from 0.1 Hz to 10 Hz. The frequency range includes both a low frequency range and a high frequency range of strong-motions. In order to evaluate strong-motions in the broadband frequency range that includes two kinds of frequency ranges whose physical characteristics are different, it is efficient that we use a different approach to simulate the strong-motions for each frequency range. Therefore the hybrid method is proposed. The hybrid method is a combination of a deterministic approach using numerical simulation methods, such as the finite difference method (FDM) (Pitarka [16], Aoi [17]) or the finite element method (FEM) (Fujiwara [18]), to evaluate strong-motions based on theoretical models obtained from the elastodynamic theory in low frequency range, and a stochastic approach using the empirical or stochastic Green's function method to evaluate strong-motions in high frequency range. Broadband strong-motions can be obtained by the superposition of low frequency strong-motions and high frequency strong-motions using matching filters.

Deterministic approach for simulating low-frequency strong-motions

Low frequency strong-motions are evaluated by solving elastodynamic equations that describe the seismic wave propagation for the physical model that consists of a characteristic source model and an underground structure model. We use numerical simulation methods, e.g. FDM and FEM to solve equations. Rapid progress of computer technology and techniques of numerical simulation enable us to solve practical problems of strong-motion evaluation. For example, in the strong-motion evaluation for earthquakes in Morimoto-Togashi fault zone, we discretize the underground structure model of domain 90km*60km*40km into 0.1km mesh from surface to depth of 4km and 0.3km mesh for the deeper part. It takes 4.5 hours to calculate 6,000 time steps for this model using our FDM code in origin 3800, 64CPU. However, if we calculate using half size of mesh for same domain, required computation time and memory size becomes 16 times and 8 times, respectively.

Stochastic approach for simulating high-frequency strong-motions

We adopt the stochastic Green's function method (Dan [19]) to evaluate high-frequency strong-motions. The stochastic Green's function method is derived based on the empirical Green's function method (Irikura [20], Irikura[21]). The empirical Green's function method is an evaluation method for strong-motion waveforms due a large earthquake using the ground motion records of earthquakes that occur in the source fault of the large earthquake as Green's functions. The empirical Green's function method is effective for evaluation of high frequency strong-motions that are strongly affected by heterogeneities of propagation paths and local site conditions. In many cases, however, we have no ground motion record of a proper earthquake which occurred in the source fault of the target large earthquake. In the stochastic Green's function method, we use functions generated by a stochastic method instead of the ground motion records for the Green's functions. The stochastic Green's function method can be applicable in the case that we have no ground motion record for the Green's function. The Green's functions used in the stochastic Green's function method are stochastically approximated and have no information on phases. The stochastic Green's function method should be used to evaluate envelope of strong-motion waveforms.

The hybrid method

In the hybrid method, we obtain broadband strong-motion waveforms by the superposition of low frequency strong-motion waveforms and high frequency strong-motion waveforms using matching filters.

The matching frequency of the hybrid method usually is set lower than 1 Hz. The matching frequency should be set a frequency in the physical transition frequency range that is between the low frequency range in which a deterministic approach is effective and the high frequency range in which stochastic approach is needed. Under the present circumstances, however, the matching frequency is often set a frequency lower than the physical transition frequency range because of the following three reasons;

(R1) Limitation of computer capacities and simulation techniques,

(R2) Limitation of modeling of rupture processes of sources,

(R3) Limitation of information on modeling of underground structures.

For the reason (R1), we can expect improvements in the future because of the rapid progress of computer technology. On the other hand, we think that the improvements for the reasons (R2) and (R3) require large efforts. In order to solve these problems, it is necessary to accumulate data obtained from seismic observation networks and surveys for underground structure and to construct databases of them.

RELATIONSHIP OF THE TWO KINDS OF HAZARD MAPS

The National Seismic Hazard Maps of Japan consists of two kinds of hazard maps. One kind of hazard map is a probabilistic seismic hazard map that shows the relation between seismic intensity value and its probability of exceedance within certain time period. The other kind of hazard map is a scenario earthquake map with a specified seismic source fault. Superimposition of the scenario earthquake maps into the probabilistic maps is considered. As the methodologies of the superimposition procedure, the following two kinds of methods are shown.

(M1) We make the two kinds of maps independently by using the different technique for strong-motion evaluation. After we complete to make the maps, we relate the scenario earthquake maps to the probabilistic hazard maps by using the "contribution factor" proposed by Kameda [22]. We call this method "weak superimposition".

(M2) We make the probabilistic seismic hazard maps by using the hybrid method for strong-motion evaluation of all possible earthquakes. Then each scenario earthquake map evaluated by using the hybrid method is regarded as a phenomenon in the probabilistic seismic hazard maps.

In the superimposition method proposed in (M1), we can select a scenario earthquake that is dominant to the strong-motion level corresponding to the probability level of interest. We can also make it clear the probabilistic position of a strong-motion due to a scenario earthquake evaluated using detailed method such as the hybrid method, by comparing the scenario seismic hazard map with the probabilistic seismic hazard maps or by comparing the strong-motion level directly with the seismic hazard curve at a site.

Under the present circumstances, we cannot adopt the methodology proposed in (M2) for the probabilistic seismic hazard analysis in the mapping project because the amount of computation for the hybrid method is too large, and also because the information that we currently have is not sufficient for precise source modeling and underground structure modeling. In the future, however, the methodology proposed in (M2) is desirable to be used for the probabilistic seismic hazard analysis in order to evaluate strong-motions more precisely. If we can adopt the methodology proposed in (M2), it is expected that we can directly locate a scenario earthquake map as a phenomenon of the probabilistic seismic hazard map and make clear the relationship of the two kinds of hazard maps.

DISCUSSION

Reliability of strong-motion level of small probability for an earthquake whose occurrence probability is high becomes a subject of discussion in preparation of the probabilistic seismic hazard maps. Strong-motion level of small probability is sometimes strongly affected by the amount of uncertainty contained in the empirical attenuation relation used in the seismic hazard analysis. We often adopt the quantity of deviation that is obtained during the statistical regression analyses to derive the attenuation relation.

However, it consists of uncertainties from various sources because the empirical attenuation relation is based on the data observed at various sites from various earthquakes. It has been pointed out that this procedure overestimates the seismic hazard because the spatial uncertainty is to be considered separately as epistemic uncertainty. On the other hand, if we use the stochastic Green's function method or the hybrid method instead of empirical attenuation relation in the strong-motion evaluation, the spatial uncertainty is not mingled and is more realistic. Further studies from both data and theory are necessary to properly quantify the uncertainty in ground motion evaluation.

The Brownian passage time distribution as well as the Poisson process is adopted for the long-term evaluation of earthquake activity by the earthquake research committee of Japan. Because of insufficiency of information on past earthquake activity in fault zones, the average recurrence interval and elapsed time since the latest earthquake event are often expressed as a time range instead of a fixed value, and consequently the occurrence probability is given by an interval. In the preliminary version of the probabilistic seismic hazard maps, based on discussion on the treatment of the probability given by an interval, we adopt the median for the typical case, and the maximum probability value for reference.

Although not only the estimated parameters but also degrees of reliability on estimation of parameters are shown in the long-term evaluation of earthquake activity, it is quite difficult to quantify the degrees of reliability, thus are not reflected in the preliminary version of the hazard maps.

Selection of a specified earthquake is essential to make a scenario earthquake map. The basic policy of the selection of a scenario earthquake in the National Seismic Hazard Mapping Project is that we choose the most probable case. However available information to determine the source parameters of the scenario earthquake is often insufficient and decision under the situation that uncertain factors are left is required. When we do not have sufficient information, we assume several cases of the characteristic source model and compare the results of them to show deviation of strong-motion evaluation due to uncertainties. It is still under consideration as problems to be solved to evaluate reliability of the results with decision under the situation that uncertain factors are left.

In order to improve the accuracy of the hybrid method, development of computer capacities and simulation techniques, improvement of modeling of rupture processes of sources, and advanced modeling of underground structures are indispensable. We can expect developments of computer capacities and simulation techniques in the future because of the rapid progress of computer technology. On the other hand, the improvements of modeling of rupture processes of sources and modeling of underground structures require large efforts. On the basis of long-term policy, it should be promoted to accumulate data obtained from seismic observation networks and surveys for underground structure and to construct databases of them.

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