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Paper:

Seismic Hazard Assessment for Japan: Reconsiderations After the 2011 Tohoku Earthquake

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Under the guidance of the Headquarters for Earthquake Research Promotion of Japan, we have been carrying out seismic hazard assessment for Japan since the 1995 Hyogo-ken Nanbu Earthquake and have made the National Seismic Hazard Maps for Japan to estimate strong motion caused by earthquakes that could occur in Japan in the future, and show estimated results on these maps. The Hazard Maps consist of two kinds of maps. One kind is a probabilistic seismic hazard map that shows the relation between seismic intensity value and its probability of exceedance within a certain period. The other kind is a scenario earthquake shaking map. In order to promote the use of the National Seismic Hazard Maps, we have developed an open Web system to provide information interactively, and have named this system the Japan Seismic Hazard Information Station (J-SHIS). The 2011 Tohoku Earthquake (Mw9.0) was the largest such event in the recorded history of Japan. This megathrust earthquake was not considered in the National Seismic Hazard Maps for Japan. Based on lessons learned from this earthquake disaster and on experience we have had in the seismic hazard mapping project of Japan, we consider problems and issues to be resolved for seismic hazard assessment and make proposals to improve seismic hazard assessment for Japan.

Keywords: seismic hazard assessment, strong ground motion, seismic hazard map, J-SHIS

1. Introduction

The Hyogo-ken Nanbu Earthquake, which struck on January 17, 1995, claimed the lives of more than 6,400 victims and brought to light many problems to be solved in Japan's earthquake disaster prevention measures. Specifically, it was pointed out regarding earthquake research that research results were not being sufficiently conveyed to the public and disaster prevention agencies. Based on lessons learned from this disaster, the Special Measure Law on Earthquake Disaster Prevention was enacted in July 1995 to promote a comprehensive national policy on earthquake disaster prevention. Pursuant to this Act, the government established the Headquarters for Earthquake Research Promotion under the Prime Minister's Office (currently under the Ministry of Education, Culture, Sports, Science and Technology (MEXT)) as special government agency with the aim of clarifying the sharing of responsibilities concerning earthquake research that must be directly linked to administrative measures, and promoting such research in a centralized manner.

The Headquarters for Earthquake Research Promotion has a Policy Committee and an Earthquake Research Committee, and is designed to undertake the following roles: (1) planning of comprehensive and basic policies, (2) coordination of budgets and other administrative work with related governmental organizations, (3) establishment of comprehensive survey and observation plans, (4) collection, arrangement, analysis, and comprehensive evaluation of survey results by related governmental organizations, universities, etc., and (5) public announcements based on comprehensive evaluations.

In April 1999, the Headquarters for Earthquake Research Promotion formulated the promotion of earthquake research: basic comprehensive policy for the promotion of earthquake observation, measurement, surveys and research (hereinafter referred to as the basic comprehensive policy) as the basic policy for the promotion of earthquake research during the next ten years and a guideline for the activity of the Headquarters for Earthquake Research Promotion.

The basic comprehensive policy sets as its basic aim to promote earthquake research that contributes to the strengthening of earthquake disaster prevention measures, especially to reducing damage caused by earthquakes. This indicates that earthquake research on the four issues below must be promoted immediately, and that surveys, observations and research required for addressing these issues must be promoted.

The four issues are as follows:

(1) Preparation of seismic hazard maps that consolidate surveys of active faults, long-term evaluation of the probability of earthquake occurrence, and strong mo-

tion prediction;

(2) Promotion of real-time transmission of earthquake information;

(3) Improvement of observation and other research in areas of intensified earthquake disaster prevention measures determined by the Act on Special Measures Concerning Countermeasures for Large-Scale Earthquakes and their vicinity;

(4) Promotion of observation and research for earthquake prediction.

Among these priority issues, the preparation of seismic hazard maps was put at the top of the list. Accordingly, the Headquarters for Earthquake Research Promotion started preparation of the National Seismic Hazard Maps for Japan, and completed and published the 2005 version in March 2005 [1].

Since then, the National Seismic Hazard Maps for Japan have been updated every year by incorporating new evaluation results. In July 2009, the Earthquake Research Committee summarized studies over the past ten years and published improved maps [2]. Notable improvements were made by adding new data and adopting advanced preparation methods, including the change of mesh resolution of maps from 1 km to a finer 250 m.

In order to contribute to preparation of seismic hazard maps, the National Research Institute for Earth Science and Disaster Prevention (NIED) launched a special project called the National Seismic Hazard Mapping Project of Japan in April 2001, and has made technical studies that contribute to preparation of seismic hazard maps, and has prepared such maps. In NIED's second five-year period, it has implemented research that contributes to advancement of seismic hazard maps through research called Strong Motion Prediction and Seismic Hazard Evaluation (FY2006-FY2007) and the Research Project on the Disaster Risk Information Platform (FY2008-).

On March 11, 2011, we had the Great East Japan Earthquake disaster caused by the 2011 Tohoku Earthquake. Responding to the 2011 Tohoku Earthquake, efforts are being made on improvement of the National Seismic Hazard Maps for Japan. As NIED project members, we consider problems and issues to be resolved for seismic hazard assessment and make proposals to improve probabilistic seismic hazard assessment for Japan based on lessons learned from this earthquake disaster and experience we have had in the seismic hazard mapping project of Japan,

2. National Seismic Hazard Maps for Japan

The National Seismic Hazard Maps for Japan are prepared to estimate strong ground motion caused by earthquakes that could occur in Japan in the future and show estimated results on these maps. The Hazard Maps consist of two kinds of maps. One kind is a probabilistic seismic hazard map that shows the relation between seismic intensity value and its probability of exceedance within a certain period. The other kind is a scenario earthquake shaking map.

Examples of probabilistic seismic hazard maps are maps of probability that JMA seismic intensity exceeds 5−, 5+, 6− and 6+ in 30 or 50 years, and maps of JMA seismic intensity corresponding to the exceedance probability of 3% and 6% in 30 years and of 2%, 5%, 10% and 39% in 50 years (**Fig. 1**). We classify earthquakes in and around Japan into three categories – characteristic subduction zone earthquakes, other subduction zone earthquakes, and crustal earthquakes. Probabilistic seismic hazard maps for three earthquake category are also evaluated.

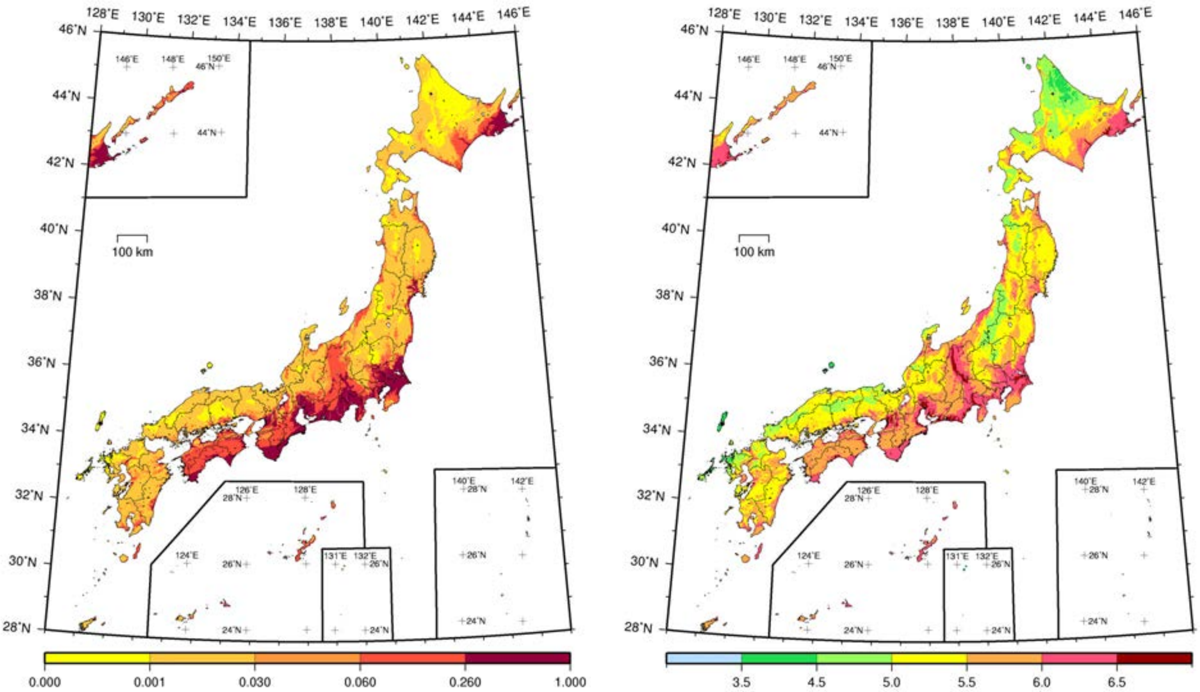
For the probabilistic seismic hazard maps, we use an empirical attenuation relation for strong-motion prediction, which follows seismic activity modeling based on long-term evaluation of seismic activity by the Earthquake Research Committee. Both peak velocities on engineering bedrock and on ground surface are evaluated for sites with approximately 0.25 km spacing based on a 7.5-arc-second engineering geomorphologic classification database. Japan Meteorological Agency (JMA) seismic intensity on the ground surface is evaluated from peak ground velocity by using an empirical formula.

The scenario earthquake shaking maps are evaluated for approximately 500 scenario earthquakes for all major active faults in Japan. Selection of a specified scenario is essential to making a scenario earthquake shake map. The basic policy of selection is that we choose the most probable case. We assume several cases of a characteristic source model and compare their results to show deviation in strong-motion evaluation due to uncertainty.

For the scenario earthquake shaking maps, based on source modeling for strong-motion evaluation, we adopt a hybrid method to simulate waveforms on engineering bedrock and peak ground velocity. The hybrid method is used to evaluate strong motion in a broadband frequency range and is a combination of a deterministic approach using numerical simulation methods, such as the finite difference method, for a low frequency range and a stochastic approach using the empirical or stochastic Green's function method for a high frequency range. Many parameters on source characterization and modeling of underground structures are required for the hybrid method. The standardization of setting parameters for the hybrid method has been studied. Under the guidance of the Earthquake Research Committee, we have summarized technical details on the hybrid method based on a recipe for strong-motion evaluation, published by the Earthquake Research Committee [2, 3].

2.1. Probabilistic Seismic Hazard Map

Probabilistic seismic hazard assessment methodology was used for preparing the probabilistic seismic hazard maps for Japan. Probabilistic seismic hazard assessment is a technique that has been developed in order to set a ground motion level corresponding to a certain probability of exceedance. Uncertainty for earthquake occurrence



Probability

(a)

JMA seismic intensity

(b)

Fig. 1. Examples of probabilistic seismic hazard map. (a) Exceedance probability within 30 years for JMA seismic intensity 6− or more. (b) JMA seismic intensity for exceedance probability 2% within 50 years.

and ground motion level are considered in probabilistic seismic hazard assessment. In the probabilistic seismic hazard maps for Japan, a map that shows the probability of exceedance for a certain ground motion level has been used as a typical map.

Seismic hazard assessment methods described below have been adopted to prepare probabilistic seismic hazard maps. In seismic hazard assessment, we analyze the relationship among three parameters: ground motion intensity that occurs in the future at a given site, the target period, and target probability. The procedure for seismic hazard assessment is briefly outlined as follows in preparation for probabilistic seismic hazard maps:

(1) Model earthquake activity around a target site according to the earthquake classification by the Earthquake Research Committee.

(2) For each modeled earthquake, evaluate the probability of the earthquake magnitude, the probability of the distance from the target site, and the probability of earthquake occurrence.

(3) Set a probability model for presuming ground motion intensity for an earthquake of a given magnitude and distance. For each modeled earthquake, evaluate the probability of the intensity of the ground motion caused by that earthquake within the target period exceeding a certain value. Use empirical attenuation relations for strong motion evaluation. Specifically, derive the peak velocity on engineering bedrock based on an attenuation relation using the shortest distance from the target site to the fault plane, then multiply the derived value by the site amplification factor to obtain the peak velocity, and then use the relation between peak velocity and JMA instrumental seismic intensity to evaluate the seismic intensity on the ground surface.

(4) Repeat the operation above for the same number of times as the number of modeled earthquakes, and sum results to obtain the probability of the intensity of ground motion occurring within the target period exceeding a certain value by at least one degree when all earthquakes are taken into consideration.

Seismic hazard assessment is thus conducted for each site, and the value of the remaining parameter is obtained by fixing any two parameters of the ground motion intensity, period, and probability. The probabilistic seismic hazard maps show the distribution of such values.

For probabilistic seismic hazard assessment, it is necessary to model all of the earthquakes that may occur in the future. Basically, based on results of long-term evaluation by the Earthquake Research Committee, we construct a model of seismic activity. Long-term evaluation is intended to be used for general disaster prevention activity, however, and it was focused to assess earthquakes considered likely to occur. The earthquakes that have been evaluated are therefore only part of the future earthquakes that may occur.

To construct the model needed to evaluate probabilistic seismic hazard, it becomes necessary to fill the gap and a model for background earthquakes is required. In probabilistic seismic hazard assessment, it has become essentially important and difficult issues to model earthquakes that have low probability of occurrence and that have not been assessed in long-term evaluation by the Earthquake Research Committee.

2.2. Scenario Earthquake Shaking Map

In addition to the probabilistic seismic hazard maps, scenario earthquake shaking maps are also prepared for earthquakes with specified source faults. For the scenario earthquake shaking maps, we adopt a numerical simulation method based on source fault modeling to evaluate strong ground motion. Using this simulation method, it is possible to calculate waveforms on the engineering bedrock layer as well as peak acceleration and peak velocity on the ground surface.

The hybrid method adopted as the simulation method for strong-motion evaluation is used to evaluate strong-motion in a broadband frequency range. It is a combination of a deterministic approach using numerical simulation methods, such as finite difference method or finite element method for a low frequency range, and a stochastic approach using the empirical or stochastic Green's function method for a high frequency range. Much information on source characterization and modeling of underground structure is required for the hybrid method. The standardization of setting parameters for the hybrid method is studied and technical details on the hybrid method are summarized as a "recipe" for strong-motion prediction of earthquakes with specified source faults, published by the Earthquake Research Committee [2, 3].

The scenario earthquake shaking maps target characteristic earthquakes that have undergone long-term evaluation by the Earthquake Research Committee. For target earthquakes that occur in major active fault zones, inner source parameters are determined and strong motion waveform is simulated using the hybrid method. Fault zones whose length in long-term evaluation is less than 20 km, which are excluded from the application of the "recipe," are excluded from target earthquakes here because the method for determining source parameters has not been established. If the occurrence probability in long-term evaluation is high, however, calculation is made for such earthquakes by exceptionally applying the current recipe. For subduction-zone earthquakes, only a strong-motion calculation using the attenuation relation is carried out, not a waveform simulation using the hybrid method, because the method for determining inner source parameters is still in the process of being improved.

Strong-motion simulation using the hybrid method targeting major active fault zones is carried out following the procedures indicated in the recipe, as briefly outlined as follows:

1) Outer and inner source parameters and subsurface structure models are determined.
2) Strong-motion waveforms on engineering bedrock are simulated.

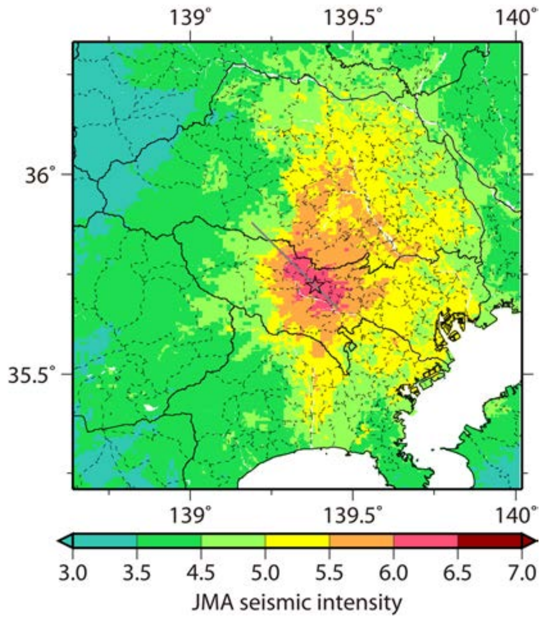


Fig. 2. Example of scenario earthquake shaking map. Distribution of JMA seismic intensity for an earthquake in the Tachikawa fault zone.

3) Ground motion on the ground surface is evaluated based on the shallow subsurface structure model.

The distribution of peak ground velocity on engineering bedrock and the distribution of the seismic intensity on the ground surface are shown on maps as results of simulation using the hybrid method (**Fig. 2**).

Areas covered by the scenario earthquake shaking maps are determined for each target fault zone. A map created by using the hybrid method covers a rectangular area including locations within a horizontal distance of about 50 km from the edges of the fault.

The target area generally encompasses an area where an earthquake of around M7 occurring in a major active fault zone is assumed to generate ground motion of intensity 5+ according to prediction results using an attenuation relation.

In all of the maps above, the site for evaluating ground motion on the ground surface is the center of each quarter mesh (about 250 m $\times$ 250 m), which is 1/16 of the third mesh (about 1 km $\times$ 1 km), within the target area. Latitudes and longitudes of maps are based on the Tokyo Datum before the revision of the Survey Act.

2.3. Modeling of Underground Structures

Once strong-motion simulation concerned, we must deal with seismic velocity-structures with attenuation. We consider deep underground structures either down to the bottom of the earth's crust or to the bottom of the plate boundary, then up to seismic bedrock with a shear-wave velocity (Vs) of 3 km/s, then farther up to the structure of an engineering bedrock layer with Vs= 400 m/s-700 m/s, and finally up to a structure of surface layers as discussed below.

(1) Crustal structure of seismic bedrock and deeper

The crustal structure of seismic bedrock and deeper indicates the structure down to the bottom of the crust or plates up to a seismic bedrock layer. Using velocity and attenuation models obtained by seismic tomography or geophysical exploration, we have been modeling this structure nationwide.

(2) Deep subsurface structure of sediments

The deep subsurface structure of sediments indicates the structure from the seismic bedrock layer up to an engineering bedrock layer with a shear velocity of 400 m/s-700 m/s. This structure strongly controls low-frequency strong-motion, so it is an important factor in the evaluation of strong low-frequency motion. For modeling of the deep subsurface structure of sediments, we use various profiles of deep boreholes, reflection and refraction surveys, data from microtremor surveys, and data from gravity surveys.

We must use an optimized modeling technique for available data sets in a target area because the quantity and quality of information on underground structure are not uniform in all areas. In the modeling of underground structure for strong-motion evaluation, seismic velocity structures are the most important parameters. It is expected that the accuracy of modeling is proportional to the quantity and quality of data. In an ideal case, we use all data to be required.

We made a three-dimensional subsurface structure model with various available data in all of Japan [4]. The depth distribution of the top depth of seismic bedrock is shown in **Fig. 3**. This includes using deep-borehole profiles for accurate structures at some sites, refraction profiles for boundary shapes in large sedimentary basins, reflection profiles for determination of boundary shapes of basin edges, data from microtremor surveys, gravity surveys and geological information for spatial interpolation. We verify and modify the structure model if necessary by using the above structure model to compare simulation results of strong motion to recorded seismograms.

It is difficult, however, to obtain sufficient data required in the above ideal procedure for 3-D modeling of velocity structures in many cases. In such a case, the only information available is from gravity surveys and geological structure information. Using these data, we estimate velocity structures indirectly. Uncertainty in velocity-structure modeling increases if we use only gravity data because gravity data represent a density structure. We thus also use information on geological structures to reduce uncertainty.

(3) Shallow subsurface structures of sediments

In the modeling of shallow subsurface structures of sediments from the engineering bedrock layer up to the ground surface, basic information consists of profiles of boreholes and data on surface geology. Surface soil structures are locally very heterogeneous and large amounts of data are required to model the surface soil structure accurately. In a case in which strong-motion evaluation for a large area is required, we adopt a rough estimation method to obtain amplification of surface soil. The site amplification factor is based on geological data and geomorphological data from Digital Nation Land Information. The mesh size of data is about 1 km. The average shear-wave velocity for the surface structure down to 30 m is estimated by using the empirical relation between microgeographical data and averaged shear-wave velocity. Site amplification factors for peak ground velocity (PGV) are then obtained from the empirical relation between averaged shear-wave velocity and PGV.

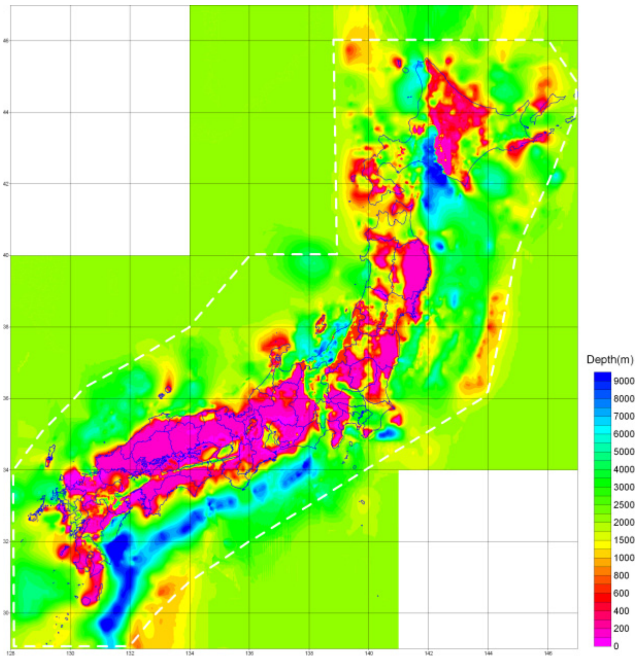


Fig. 3. Depth distribution of top depth of seismic bedrock.

If there is sufficient information on surface soil structures, we adopt a more accurate method, instead of a rough method, in which we model the surface soil velocity structure for each mesh using as many boring profiles and as much geological data as possible.

2.4. Japan Seismic Hazard Information Station (J-SHIS)

National Seismic Hazard Maps for Japan are regarded as a comprehensive compilation of products of the Headquarters for Earthquake Research Promotion for seismic hazard assessment in Japan and include data required for mapping such as seismic activity models, seismic source fault models, and subsurface structure models and site amplification models. These models contain an enormous amount of information. As a part of studies on the utilization of seismic hazard maps, we set up a Committee on Engineering Application of National Seismic Hazard Maps for Japan to explore the issue. The Committee's report [5] recommended that seismic hazard maps must be considered as seismic hazard information sharing bases by regarding maps as a group of information incorporating underlying data used in the evaluation process, such as seismic activity models, seismic source models, and subsurface structure models, rather than mere maps as final products. In order to put this recommendation into practice, we developed an online disclosure system for seismic hazard maps, and started its operation in May 2005 as the Japan Seismic Hazard Information Station (J-SHIS), which was the name proposed in the report above.

Since we launched operation of the J-SHIS, remarkable progress had been made in technology to distribute map data via the Internet. By incorporating the latest technology, we developed a new J-SHIS system in July 2009[1] (**Fig. 4**). The new system manages various data in an integrated manner, including new national seismic hazard maps for Japan that consist of the probabilistic seismic hazard maps for Japan nationwide with a 250 m mesh resolution and the scenario earthquake shaking maps based on detailed strong motion prediction of earthquakes that occur at major active fault zones, as well as deep subsurface structure models and 250 m mesh geomorphological land classification models used for required calculations. The system is also capable of providing these data in a user-friendly manner by showing them over background maps. This new J-SHIS system is a Web mapping system based on open source software that enables general users to easily view various data on their Internet browsers. Notable new functions available include the following:

- Image overlapping functions such as the layer transparency function between the seismic hazard maps and Google Maps
- A scroll function that enables users to move maps and to freely scale maps as they zoom in or out
- A seismic hazard map viewing function supporting a 250 m mesh resolution
- A detailed location search function using addresses and postal codes
- A function to display a seismic source fault on the browser
- A function to display attribute values for each mesh

After the 2011 Tohoku Earthquake, the need to promote understanding of seismic hazard assessment itself has increased. We therefore added a new function to the J-SHIS that was developed mainly as a viewer for the National Seismic Hazard Maps for Japan since October 2011 and J-SHIS had been renewed as a portal site on the seismic hazard information in Japan. In a 2012 update, a J-SHIS Web application programming interface (API) has been developed to promote the utilization of J-SHIS data in an interoperable system. Applications on smart phones that use J-SHIS data have been published. The development of J-SHIS functions is thus progressing as a basis for transmitting seismic hazard information to various entities.

1. http://www.jshis.bosai.go.jp

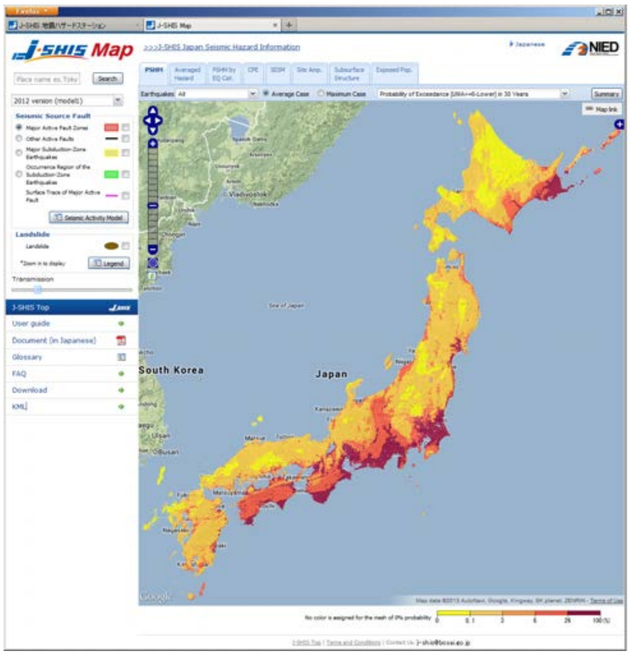


Fig. 4. Example of screenshot of J-SHIS.

3. Reconsideration of Seismic Hazard Assessment After the 2011 Tohoku Earthquake

The 2011 Tohoku Earthquake (Mw9.0) was the first M9-class earthquake to be recorded by a dense seismograph network. Ground motions were recorded at more than 1,200 K-NET [6] and KiK-net [7] stations. The Peak ground accelerations (PGAs) exceeded 1 g at 20 sites and the largest PGA, 2,933 gals, was observed at K-NET Tsukidate station (MYG004). **Fig. 5** compares observed JMA seismic intensity of the 2011 Tohoku Earthquake and JMA seismic intensity distribution for a 2% probability of exceedance in 50 years, which is one of the probabilistic seismic hazard maps. In the probabilistic seismic hazard map, the seismic intensity of 2% probability of exceedance in 50 years has been evaluated as 6− or 6+ in Miyagi prefecture and in the southern Kanto region, which covers most observed ground motion for the earthquake. In Fukushima Prefecture and northern Ibaraki Prefecture, however, where large earthquakes with a high probability of occurrence had not been expected, seismic intensity 6+ was observed at points where seismic intensity 5− or 5+ was expected on the seismic hazard map. As observed in this comparison, the predicted ground motion level of the probabilistic seismic hazard map was clearly underestimated in these areas. This is primarily because, in the long-term evaluation that has been the basis of the seismic activity model for probabilistic seismic hazard assessment, the occurrence of great earthquakes of M9.0 has not been evaluated. The cause of underestimation also lies, however, in an inability to establish the whole framework of probabilistic seismic hazard assessment methods well under circumstances in which many issues are left unresolved in seismology.

It is necessary for probabilistic seismic hazard assess-

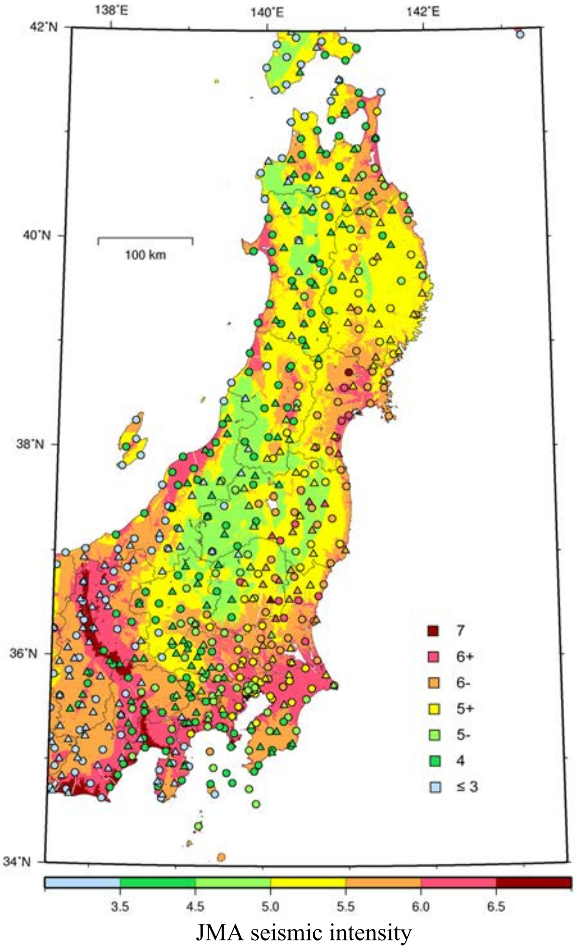
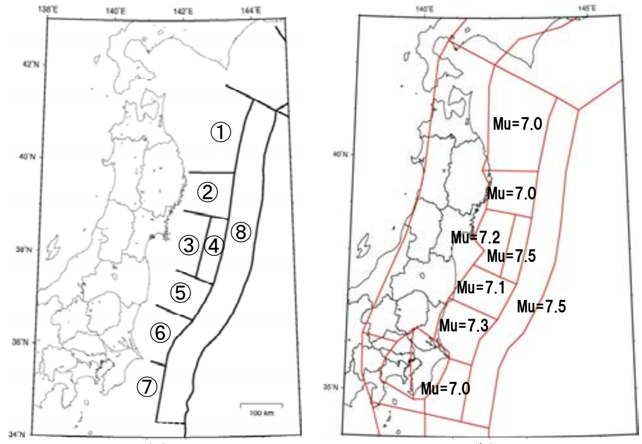


Fig. 5. Comparison between observed JMA seismic intensity（○：K-NET, △：KiK-net）of the Tohoku earthquake and JMA seismic intensity distribution for 2% probability of exceedance in 50 years, which is one of the probabilistic seismic hazard maps of the 2010 version.

Table 1. Long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso before the 2011 Tohoku Earthquake.

Region	Magnitude	Occur. prob. within 30 years
①	Approx. M8.0	0.2%-10%
	M7.1-M7.6	About 90%
②	Unknown	Unknown
③	Approx. M7.5	99%
④	Approx. M7.7	80%-90%
⑤	Approx. M7.4	About 7% or less
⑥	M6.7-M7.2	About 90% or more
⑦	Unknown	Unknown
⑧	Approx. Mt8.2 (Tsunami earthquake)	About 20%
	Approx. M8.2 (normal fault type)	4%-7%



(a) (b)

Fig. 6. (a) Target areas for Long-term evaluation of seismic activity for the region from off Sanriku to off Boso. (b) Upper limit of magnitude Mu for background earthquakes for the Pacific plate.

ment to model all of the earthquakes that may occur in the future. We had, however, constructed a model of seismic activity for probabilistic seismic hazard assessment based on the results of the long-term evaluation by the Headquarters for Earthquake Research Promotion. Long-term evaluation was intended to be used for general disaster prevention and it focused on assessing earthquakes considered most likely to occur, so earthquakes that had been evaluated were only parts of future earthquakes that could occur.

Based on lessons learned from the earthquake disaster, we understood that it was necessary to fill the gap by considering low probability earthquakes or background earthquakes in order to construct the complete model needed to evaluate probabilistic seismic hazard. Now we recognize that it is essential for probabilistic seismic hazard assessment to consider earthquakes that have a low probability of occurrence and have not been assessed in long-term evaluation by the Headquarters for Earthquake Research Promotion.

To examine more specific issues, we summarized the seismic activity model used for the probabilistic seismic hazard maps before the 2011 Tohoku Earthquake. For source fault regions of the 2011 Tohoku earthquake, the model had been implemented based on the Long-term evaluation of seismic activity for the region from off Sanriku to off Boso [8].

In long-term evaluation, the entire area was divided into eight regions and seismic activity had been evaluated in each region in **Fig. 6(a)**. Long-term evaluation results are summarized in **Table 1**. Based on records of past earthquakes, we analyzed patterns of occurrence to evaluate typical earthquakes for each region. For regions where the presence of a specific size of earthquake was observed, the size of earthquakes and the interval between earthquakes were evaluated. Typical examples included the Off Miyagi earthquake. In the long-term evaluation conducted before the 2011 Tohoku Earthquake, earthquake occurrence had been evaluated based on the idea that large earthquakes of the same size occur repeatedly in the same area, based on observed records, historical documents and results of geomorphological and geological surveys.

The probabilities of earthquake occurrence were calculated by assuming a Poisson process without specifying source faults for areas where it was difficult to evaluate earthquake occurrence because of a lack of data. In addition, for regions where evidence of past earthquakes was not clear, such as the off Boso area, no specific assessment was made and evaluation results were shown as unknown.

A significant point, however, in the long-term evaluation of seismic activity for the region from off Sanriku to off Boso was to show that magnitude 8.2 tsunami earthquakes had been expected to occur with a probability of 20% in the next 30 years in the region near the Japan Trench from the north off Sanriku to off Boso. If measures had been taken for tsunami earthquakes based on this evaluation, we may have been able to reduce some of the damage of this earthquake, especially in regions south of Fukushima prefecture.

For the probabilistic seismic hazard maps, in addition to earthquakes related to the above long-term evaluation, earthquakes that were not even mentioned in long-term evaluation were considered as background earthquakes. Background earthquakes for the Pacific plate are shown in **Fig. 6(b)**. In these regions, interplate earthquakes that occur on the upper boundary of the Pacific plate and intraplate earthquakes on the Pacific plate have been considered. The upper limit of magnitude of the background earthquakes had been set for each region, determined by the maximum size of historical earthquakes occurring in areas before the 2011 Tohoku earthquake, excluding large earthquakes considered in the long-term evaluation. In this regard, it had been pointed out that to use the previous maximum value for each region might lead to an underestimated result. There were many opposing views for setting an upper limit exceeding the previous largest event before the 2011 Tohoku Earthquake.

Based on lessons from the 2011 Tohoku Earthquake, the revision of long-term evaluation methodology has been promoted [9, 10]. In previous long-term evaluation, based on observation data, historical records and the results of geological and topographic surveys, earthquakes have been evaluated by assuming that those of similar size occur repeatedly in the same area. In the next long-term evaluation, it has been aimed by improving methodology to take into account both earthquakes that can be estimated from seismic data obtained in the past and earthquakes that have not been confirmed by historical records and observations, based on scientific evidence. After techniques of long-term evaluation have been improved, we expect that many earthquakes that may occur in the future will be covered by the new long-term evaluation.

It may be difficult, however, to completely evaluate all possible earthquakes in the future by using techniques for long-term evaluation based on scientific methodology and scientific knowledge, such as observational records, historical records and the results of geological and topographic surveys. In probabilistic seismic hazard assessment, a framework for considering the uncertainty of the phenomenon itself and the limits of scientific knowledge has been prepared based on the stochastic and probabilistic method. It becomes an important issue to establish a methodology to make the framework work effectively. In order to construct a probabilistic seismic activity model that encompasses the seismic activity of all possible earthquakes, it is necessary to establish a new methodology from that of conventional long-term evaluation. To achieve this, it may be necessary to objectively evaluate the property of long-term evaluation in the modeling of seismic activity for seismic hazard assessment.

It may also be necessary to promote appropriate modeling of background earthquakes that encompasses all earthquakes that are not considered in long-term evaluation. It may, for example, be possible to evaluate the magnitude of earthquakes from the area of the plate boundary that can be considered to cause earthquakes and to assess the frequency of earthquakes by using the Gutenberg-Richter law that shows the relationship between the number of earthquakes and their magnitude. In the revision of long-term evaluation methodology, it is essential to consider a new method of setting the scale for earthquakes that is not limited by using the historical largest event for each small region.

After the 2011 Tohoku earthquake, the Earthquake Research Committee reviewed long-term evaluation for the area in November 2011 in which the 2011 event occurred and released a revised version of long-term evaluation of seismic activity for the region from off Sanriku to off Boso. Although this revision has not yet been made itself and for the most part has remained a traditional evaluation, a new assessment has been made of 2011 Tohoku type earthquakes. Based on this evaluation, we revised seismic hazard assessment.

Based on lessons learned from the 2011 earthquake, we are working on improving seismic hazard assessment using several policies. The basic strategy for improvement is that we consider large earthquakes not evaluated by long-term evaluation by taking into account remaining uncertainty. To validate long-term evaluation itself, we built a seismic activity model based on the Gutenberg-Richter law and used the model as a comparative reference. For these reasons, we consider the following three models:

Model 1, made using conventional methods for comparison with the improved model

Model 2, incorporating new thinking improved taking into account uncertainty based on our experience with the 2011 Tohoku Earthquake,

Model 3, based on the Gutenberg-Richter law as a reference for checking the validity of models built based on long-term evaluation

Table 2 shows parameters of the three seismic activity models in the region from off Sanriku to off Boso. Model 1 complies with revised long-term evaluation. Regarding background earthquakes for regions ②-⑧ in **Fig. 6(a)**, the maximum magnitude (Mu) of interplate earthquakes is 8.0 and the Mu of intraplate earthquakes is 7.5. Model 2 is an improved version of Model 1 in

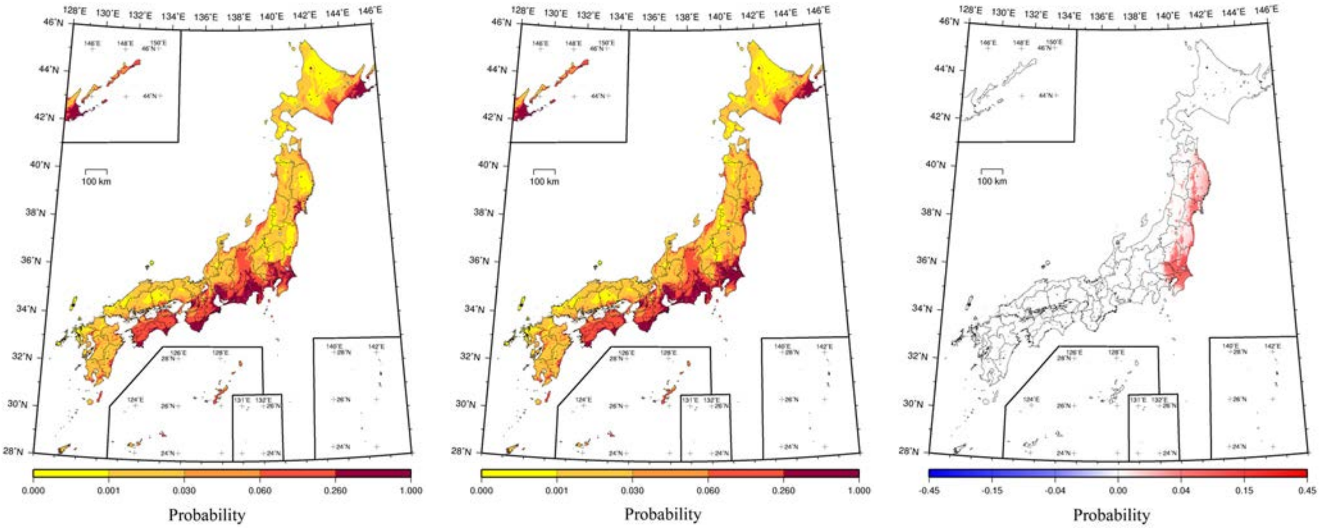
Table 2. Seismic activity model based on revision of long-term evaluation.

	Earthquake type	Previous model	Revised Model 1	Revised Model 2	Revised Model 3
(0)	Repeating Eq.	None	M[1] =8.4-9.0 P30[2] =0%	M=8.4-9.0 P30=0%	Model based on the Gutenberg-Richter law with Poisson process for total area Interplate Eq. Mu=9.5 Intraplate Eq. Mu=8.2
①	Repeating Eq.	M=8.0 P30=6.3%	M=8.0 P30=7.3%	M=8.0 P30=7.3%	
①	Other Eq.	M=7.1-7.6 P30=93%(P)[3]	M=7.1-7.6 P30=88%(P)	M=7.1-7.6 P30=88%(P)	
①	Background Eq.	Mu=7.0	Mu=7.0	Mu=7.0	
②	Repeating Eq.	None	None	None	
②	Other Eq.	None	None	None	
②	Background Eq.	Mu=7.0	Mu=8.0/7.5[4]	Mu=8.2/8.2	
③	Repeating Eq.	M=7.5 P30=100%	M=7.4 P30=55%(P)	None	
③	Other Eq.	None	M=7.0-7.3 P30=61%(P)	None	
③	Background Eq.	Mu=7.2	Mu=8.0/7.5	Mu=8.4/8.2	
④	Repeating Eq.	M=7.7 P30=81%	M=7.9 P30=0	Combined with ③	
④	Other Eq.	None	M=7.2-7.6 P30=51%(P)		
④	Background Eq.	Mu=7.5	Mu=8.0/7.5		
⑤	Repeating Eq.	M=7.4 P30=7.2%(P)	M=7.4 P30=14%(P)	None	
⑤	Other Eq.	None	None	None	
⑤	Background Eq.	Mu=7.1	Mu=8.0/7.5	Mu=8.2/8.2	
⑥	Repeating Eq.	M=7.0 P30=99%	M=7.0 P30=95%	None	
⑥	Other Eq.	None	M=6.9-7.6 P30=69%(P)	None	
⑥	Background Eq.	Mu=7.3	Mu=8.0/7.5	Mu=8.3/8.2	
⑦	Repeating Eq.	None	None	None	
⑦	Other Eq.	None	None	None	
⑦	Background Eq.	Mu=7.0	Mu=8.0/7.5	Mu=8.3/8.2	
⑧	Repeating Tsunami Eq.	M=8.2(6.8) P30=20%(P)	Mt[5] =8.6-9.0 P30=25%(P)	Mt=8.6-9.0 P30=25%(P)	
⑧	Repeating Eq. (Normal fault)	M=8.2 P30=5.1%(P)	M=8.2 P30=5.1%(P)	M=8.2 P30=5.1%(P)	
⑧	Other Eq.	None	None	None	
⑧	Background Eq.	Mu=7.5	Mu=8.0/None	Mu=8.0/None	

(0) Source fault area for the 2011 Tohoku type earthquakes.
1) M is JMA magnitude.
2) P30 is the occurrence probability within 30 years.
3) (P) shows that occurrence probability is calculated assuming a Poisson process.
4) Mu is the upper limit of magnitude. Mu= Interplate Eq. / Intraplate Eq.
5) Mt is tsunami magnitude.

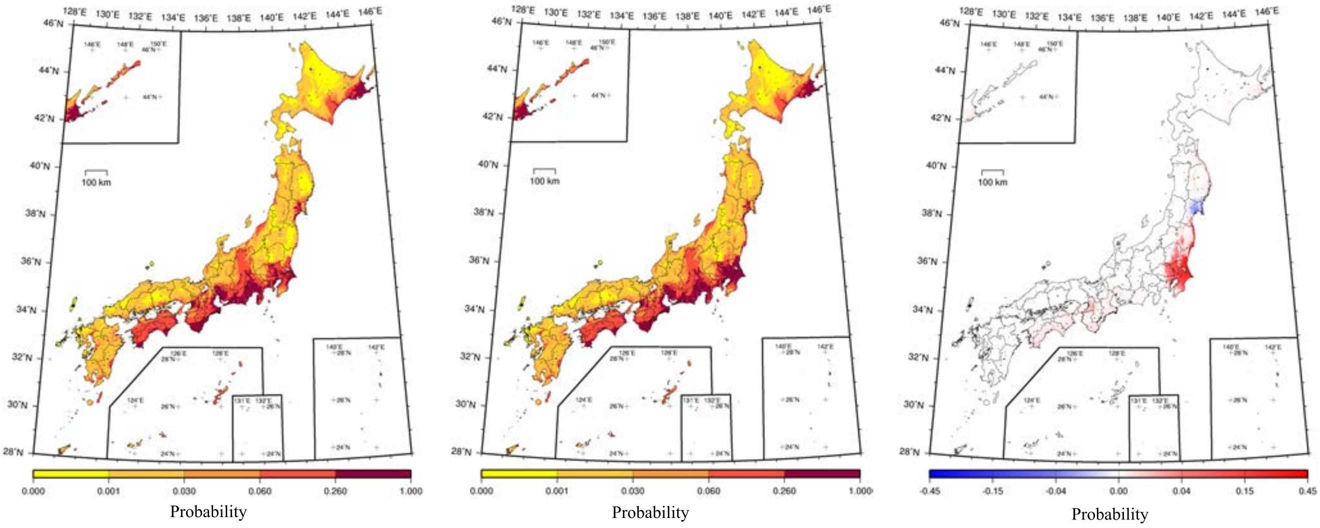
which, for background earthquakes, the Mu of an interpolate earthquake is the maximum magnitude calculated from the size of the area and the Mu of intraplate earthquakes is 8.2. In Model 3, the Gutenberg-Richter law is applied without using results of long-term evaluation to one large area for all of the combined area of ①-⑧ in **Fig. 6(a)**. The Mu for interplate earthquakes is 9.5 and that for intraplate earthquakes is 8.2. To see the impact of earthquakes similar to the 2011 Tohoku type that is considered in Model 1, we also made a map as of January 1, 2011, just before the earthquake occurred. For 2011 Tohoku type earthquakes, the probability of occurrence over the next 30 years is approximately 15%, assuming an average occurrence interval of 600 years and 561 years from the latest activity and $\alpha = 0.24$ for the Brownian passage time (BPT) distribution model.

Figure 7 compares the 2011 version and modified 2011 version with the 2011 Tohoku type. Maps show the distribution of exceedance probability within 30 years for JMA seismic intensity 6−. From this comparison, taking quakes similar to the 2011 Tohoku type into consideration, it becomes apparent that the capability of underestimating the hazard level in Fukushima prefecture and northern Ibaraki prefecture has been improved – i.e.,



(a) (b) (c)

Fig. 7. Maps of the distribution of exceedance probability within 30 years for JMA seismic intensity 6−. (a) 2011 version. (b) Modified 2011 version with the earthquakes of the 2011 Tohoku type. (c) Differences between (a) and (b).



(a) (b) (c)

Fig. 8. (a) 2011 version. (b) Model 1 of the tentative 2012 version. (c) Differences between (a) and (b).

the reason for underestimating ground motion hazard in Fukushima prefecture and northern Ibaraki prefecture is that quakes similar to the 2011 Tohoku type have not been included in the long-term evaluation. This means that if an appropriate seismic activity model is given, it is shown that appropriate ground motion hazard assessment is possible in the basic framework of probabilistic seismic hazard assessment by using the current methodology.

Figure 8 compares the 2011 version and Model 1 of the 2012 tentative version, showing changes in hazard level before and after the 2011 Tohoku Earthquake in evaluation using the conventional method. Immediately after the 2011 Tohoku Earthquake occurred, the hazard level of ground motion in the Kanto region rose. One reason for this is that we raised the value of the maximum M of background earthquakes to 8.0 based on a judgment in discussion that the uncertainty of seismic activity in the region has been growing since the 2011 Tohoku Earthquake.

Figure 9 compares Models 1, 2 and 3 based on lessons from the 2011 Tohoku Earthquake. In addition to Model 1 made using the conventional method, we consider improved Model 2 taking into account uncertainty of seismic activity models and Model 3 for which, based on the Gutenberg-Richter law, very large earthquakes up to M9.5 are included. It is understood that uncertainty in seismic activity models is increasing in the order Models 1, 2 and 3. Reflecting this, the hazard level in the low probability portion is increased. To reduce uncertainty in the seismic activity model as possible has been a challenge to improve reliability of the hazard assessment in the low probability.

We considered the issue of representation of ground motion hazard caused by earthquakes of low frequency. Many subduction earthquakes occur at intervals of from decades to centuries. On the other hand, many earth-

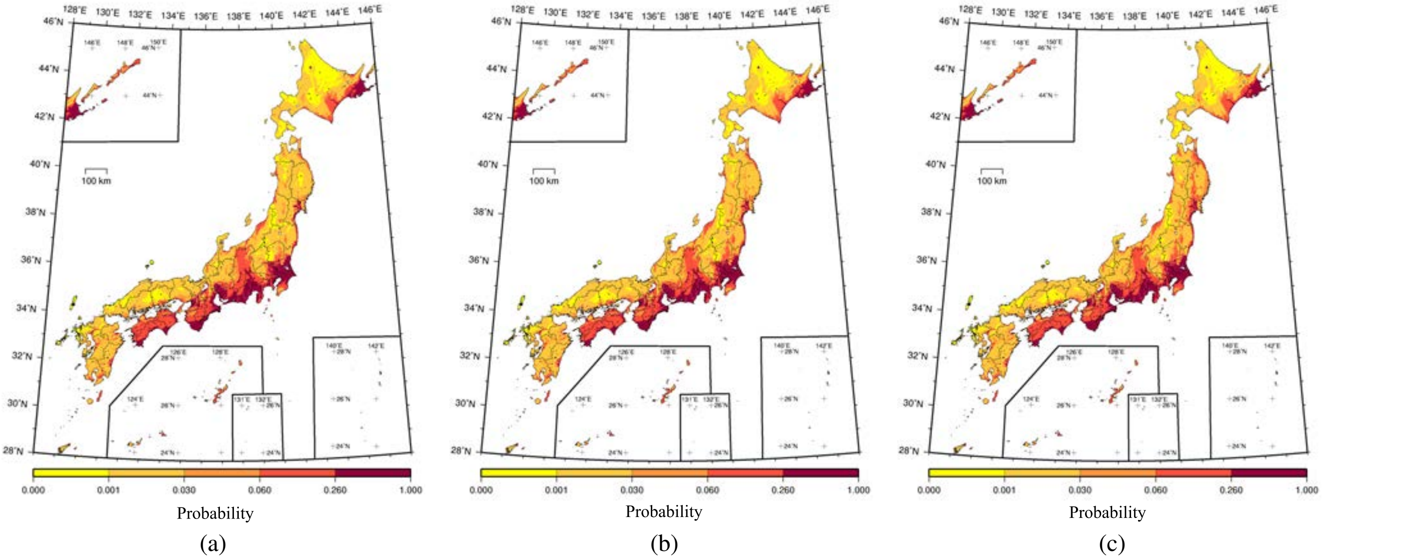


Fig. 9. Comparison of (a) Model 1, (b) Model 2 and (c) Model 3.

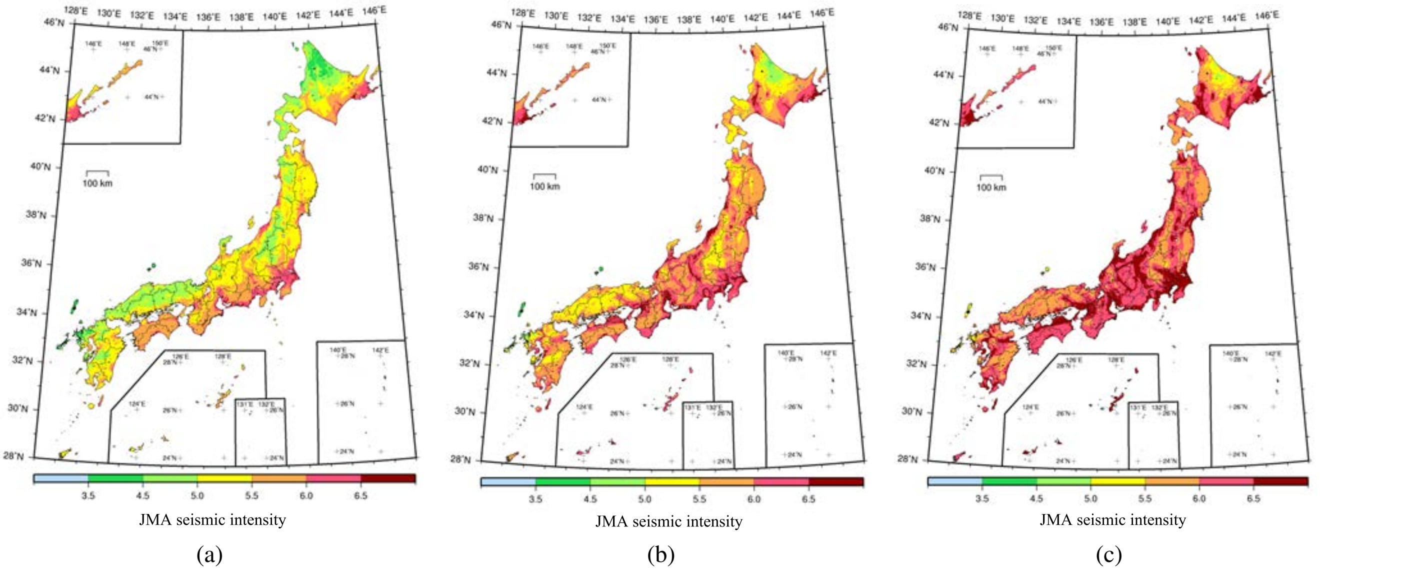


Fig. 10. Maps of the distribution of seismic intensity corresponding to a return period of (a) 1,000 years, (b) 10,000 years and (c) 100,000 years. The map for 10,000 years indicates the degree of shaking caused by both subduction zone earthquakes and earthquakes in major fault zones. The map for 100,000 years shows the degree of shaking for most shallow inland crustal earthquakes, including background earthquakes.

quakes due to active faults in inland and coastal areas occur at intervals of from thousands to several tens of thousands of years, for which reason the probability expression for short-return periods, the probability for earthquakes due to active faults in coastal areas and inland becomes much smaller. Using the representation for an emphasis on urgency, it is difficult to show the effect of them appropriately. To overcome these problems, we try to make probabilistic seismic hazard maps for very long return periods and to visualize ground motion hazard by earthquakes with low occurrence probability in active faults.

Based on seismic hazard assessment averaged over a long period, we make maps showing the distribution of seismic intensity corresponding to long return periods. To do this, we evaluate hazard by using a Poisson process for all seismic activity. We calculate return periods for 1,000, 10,000 and 100,000 years. **Fig. 10** shows maps for seismic intensity distribution for return periods of (a) 1,000 (b) 10,000, and (c) 100,000 years. The map for a return period of 1,000 years indicates that the degree of shaking is mainly caused by subduction zone earthquakes. The map for 10,000 years indicates that the degree of shaking is caused by both subduction zone earthquakes and earthquakes in major fault zones. The map for 100,000 years shows that the degree of shaking is mostly due to shallow inland crustal earthquakes, including background earthquakes. For long return periods, we conclude that it could be hit by shaking of seismic intensity 6− or more in almost all regions of Japan.

4. Conclusions

We have revised seismic hazard assessment based on a revised version of long-term evaluation of seismic activity for the region from off Sanriku to off Boso by the Earthquake Research Committee. A seismic activity model for other regions of Japan is also being revised [9, 10]. After the revision of long-term evaluation for all of Japan, we will recalculate seismic hazard. The following five problems remain to be solved:

(1) Modeling of seismic activity with no oversight for low-probability earthquakes

For both subduction zone earthquakes and earthquakes at active faults, it is necessary to model seismic activity considered to involve events once every several thousand or several tens of thousands of years. To do so, we must model earthquakes with a low probability of occurrence using the Gutenberg-Richter law or other statistical techniques to compensate for insufficient aspects of long-term evaluation.

(2) Assessment of strong ground motion considering low-probability earthquakes

In addition to emphasizing the urgency of earthquake occurrence by showing seismic hazard probability, we must prepare maps that show strong-motion levels based on averaged long-term seismic hazard assessment. Based on averaged long-term seismic hazard assessment, for example, evaluating strong-motion levels for 10,000-100,000 year return periods, we must prepare maps that show the distribution of strong-motion levels that represent the effect of major earthquakes on active faults and subduction zone earthquakes with low probability. Regarding current seismic hazard assessment for low probability, it is not enough to evaluate uncertainty for low-probability M8 class earthquakes and it is necessary to improve techniques for evaluating these earthquakes.

In this study, we have considered problems associated with (1) and (2), above, as issues raised by the 2011 Tohoku Earthquake. In the future, problems (1) and (2) must be solved systematically in national seismic hazard assessment. Although it has not been considered in this study, however, three questions remain.

(3) Development of methodology for complementary use of probabilistic seismic hazard maps and the scenario earthquake shaking maps.

It is necessary for purposes of earthquake preparedness to establish a methodology through which appropriate scenario earthquakes are selected from probabilistic seismic activity models.

(4) Sophistication of techniques for predicting strong-motion for mega earthquakes

In assessing seismic hazard considering low-probability events, it is necessary to predict strong-motion for mega earthquakes. The recipe for prediction strong-motion currently being used in Japan, however, covers only subduction zone earthquakes up to about M8 and earthquakes on active faults up to about 80 km long. Techniques applied to the prediction of strong-motion for super large earthquakes must thus be made more sophisticated.

(5) Sophistication of utilization and transmission of seismic hazard information

In addition to improving seismic hazard assessment itself, it is necessary in using seismic hazard information to consider how to make hazard information meaningful. As one measure for doing so, we address enhancement of Seismic Hazard Information Station J-SHIS.

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