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PROBABILISTIC TSUNAMI HAZARD ASSESSMENT ALONG THE COAST OF JAPAN: FAULT MODELS AND TSUNAMI SIMULATION

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Abstract

The National Research Institute for Earth Science and Disaster Resilience (NIED) in Japan is conducting a probabilistic tsunami hazard assessment (PTHA) along the coast of Japan (Fujiwara et al., 2013). To cover all future potential earthquakes and related tsunamis that may occur in and around Japan, we constructed approximately 10 000 characterized fault models (CFMs) for subduction-zone earthquakes in the Japan Trench, Nankai Trough, and Sagami Trough. The Tsunami Recipe of the Headquarters for Earthquake Research Promotion (2017) was used to construct the CFMs. The first step in the construction of the CFMs involved the preparation of element faults with a length and width of approximately 5 km to account for fault slips on the curved surfaces of subducting plates. The strike, dip, and depth of the element faults were determined by the method of least squares such that the element faults could cover the plate boundary surface. The slip angle of each element fault was determined based on the direction of the relative motion between the Pacific and North American plates in the Japan Trench, and between the Philippine Sea and North American plates in the Nankai and Sagami troughs (Loveless and Meade, 2010). Slip heterogeneities in the CFMs were expressed by a combination of three types of slip area: background, large, and super large. The large slip area had twice the average slip amount of the total fault area and corresponded to 30% of the total fault area, whereas the super-large slip area had four times the average slip amount of the total fault area and corresponded to 10% of total fault area. The super-large slip areas were set when the fault area reached the trench. After the crustal deformation was calculated using Okada’s formula (1992) for each CFM, we applied a Kajiura’s filter (1963) to the calculated crustal deformation to obtain the initial surface water displacement. Subsequently, a tsunami simulation was carried out based on the nonlinear longwave equation using a nesting grid system. The rupture processes of earthquakes were not taken into consideration because we placed a high priority on a comprehensive tsunami hazard assessment for Japan. After the tsunami simulation was performed, the tsunami heights were extracted along the coast of Japan. Tsunami hazard curves at specific coastal points were then calculated based on the tsunami heights and the probability of earthquake occurrence. These tsunami hazard curves indicate the probability of the maximum tsunami height exceeding the related tsunami level within a specific period of time. The exceedance probability in 30 years from now at the representative points was found to be high along the Japan Trench and Nankai Trough but relatively small along the Sagami Trough. Future research will undertake PTHAs for other sea areas to obtain a comprehensive PTHA for Japan.

Keywords: Probabilistic tsunami hazard assessment (PTHA); Characterized fault model (CFM); Tsunami simulation

1. Introduction

After the magnitude 9.0 Tohoku earthquake in Japan on March 11, 2011, it was recognized that a scenario-type approach for tsunami hazard assessments may include little information regarding likelihoods. In addition, some limitations exist in terms of the ability of such an approach to cover all types of tsunami hazard. A probabilistic approach was therefore introduced within the tsunami hazard assessment methodology to estimate the probability that a specific tsunami height will exceed a given value at a specific location in a given number of years. In 2012, the National Research Institute for Earth Science and Disaster Resilience (NIED) in Japan began a research project on the probabilistic tsunami hazard assessment (PTHA) of Japan's coast [1]. After numerous years of research on the PTHA, the "Probabilistic hazard assessment of tsunamis due to large earthquakes along the Nankai trough" [2] was published by the Headquarters for Earthquake Research Promotion (HERP) in 2020. This was the first time that the probability of tsunami hazard information had become openly available to the general public in Japan to facilitate tsunami disaster prevention measures.

A PTHA consists primarily of three components: the construction of fault models, tsunami simulations, and the analysis of hazard curves—all of which are dealt with in the present study. This paper first explains the procedure for setting-up element faults. We then describe how to construct simplified fault models, termed 'characterized fault models' (CFMs), based on the long-term evaluation by the HERP to cover various types of possible earthquakes around the Japanese islands. The bathymetry data that were used for the tsunami simulations are presented, and the simulations and calculation of the tsunami height along the coast are described. In connection with the results of the tsunami simulations, the relationship between the slip pattern of the CFMs and the tsunami height distribution along the coast are discussed. Based on the distribution of tsunami heights along the coast (in the Japan Trench, Nankai Trough, and Sagami Trough), hazard curves for representative locations are presented. Finally, the characteristics of the hazard curves are discussed to consider the earthquake groups that might represent a potential future risk.

2. CFM

Although it is expected that an earthquake has heterogeneities in the slip distribution, it is a formidable task to take account of every pattern of slip heterogeneities in fault models and to then conduct tsunami simulations for all of those models. We therefore simplify the slip distribution through a characterized process and define this simplified fault model as a CFM. This simplification of heterogeneous slip distribution can help to reduce the number of fault models to be constructed as well as the computational cost of the tsunami simulations, thus making it possible to conduct a comprehensive PTHA for Japan.

2.1 Element faults

The first step of constructing the CFMs involved preparing element faults with a constant length of approximately 5 km and a variable width depending on the dip angle of the element faults. The element faults were configured on the surface of the subducting plate to account for the fault planes on its 3-D undulating surface. The slip angle of each element fault was determined on the basis of the direction of the relative motion between the subducting plate and the continental plate [3]. The element faults were extracted by the source area and large slip area, which are described in Section 2.2, and once extracted, produced the fault parameters for the tsunami simulation.

2.2 CFM construction

Once the element faults were prepared, we constructed thousands of CFMs mainly for subduction-zone earthquakes in the Japan Trench, Nankai Trough, and Sagami Trough based on the Tsunami Recipe [4] that was created by the HERP. A CFM consists of three different slip areas: "background slip area", "large slip area", and "super-large slip area". The large slip area has twice the average slip amount and 30% of the total fault area, whereas the super-large slip area has four times the average slip amount and 10% of the total fault area. The background slip area has a slip amount corresponding to the residual seismic moment. CFMs with one source area have many large slip areas with various locations, which are placed at approximately half pitch intervals. If the fault area reaches the trench, a “super-large slip area” may be incorporated to represent an extremely large slip along the trench. The aspect ratio of the large slip area and super-large slip area is set to approximately two, and the overlap ratio between neighboring large slip areas is approximately 50%.

2.3 Japan Trench

Earthquakes that have occurred along the Japan Trench were categorized into numerous groups according to the long-term evaluation [5]. These groups included the great Tohoku earthquake type, tsunami earthquake type, intraplate earthquake type, and earthquakes off northern Sanriku, which were all modeled as specified earthquakes. Other interlocking earthquake types—the largest-class earthquake type and unspecified earthquake type—on the other hand, were modeled as unspecified earthquakes. The total number of CFMs along the Japan Trench amounted to approximately 1900. Examples of the CFMs that belong to the great Tohoku earthquake type are shown in Fig. 1.

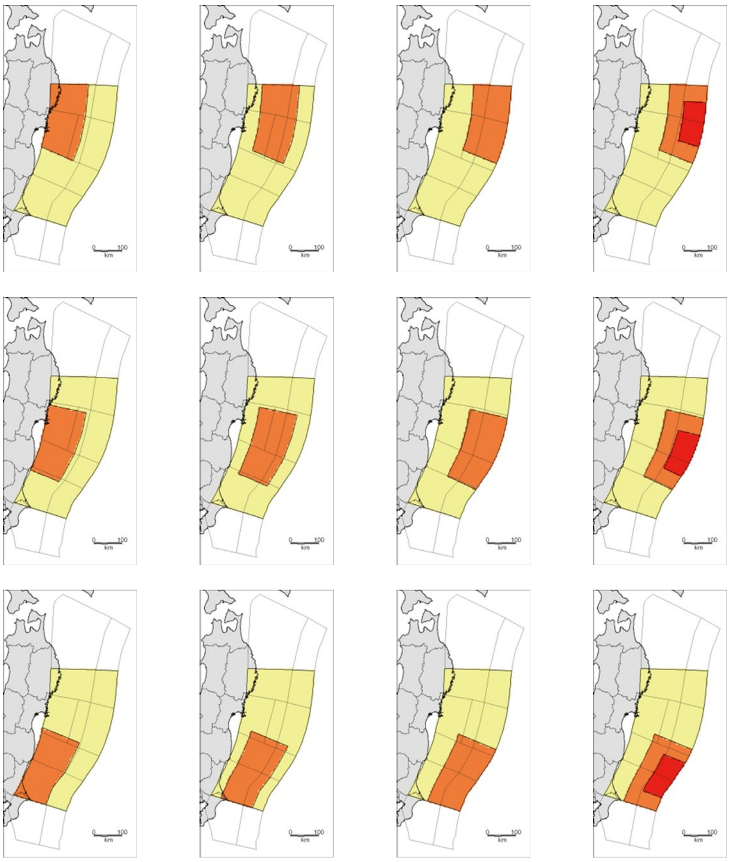

Fig. 1 – Examples of the characterized fault models (CFMs) that belong to the great Tohoku earthquake type along the Japan Trench. The red, orange, and yellow colors denote the super-large slip area, large slip area, and background slip area, respectively. The CFMs on the far right-hand-side include the super-large slip area. The grey lines indicate the hypothetical source areas defined by the Headquarters for Earthquake Research Promotion (HERP).

2.4 Nankai Trough

CFMs along the Nankai Trough were constructed based on the long-term evaluation by the HERP [6]. The long-term evaluation illustrates 15 examples of hypothetical source regions along the Nankai Trough, and various large slip areas were configured by shifting a half pitch interval for each of the 15 source regions to construct basic CFMs. The parameters of the basic CFMs were set according to the Tsunami Recipe [4]. In addition to the basic CFMs, extended CFMs with source regions that were created by combining the hypothetical regions defined by the long-term evaluation were constructed in the same way. The total number of CFMs along the Nankai Trough amounted to approximately 3500. Examples of the basic CFMs along the Nankai Trough are displayed in Fig. 2.

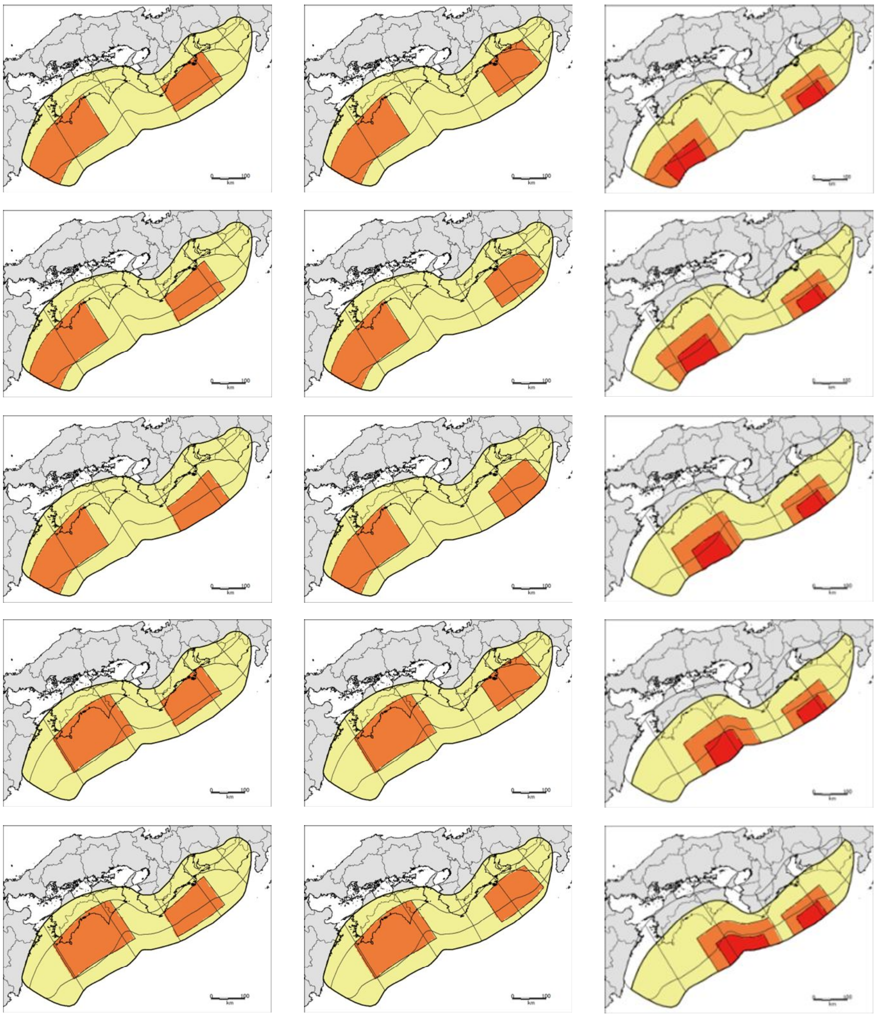

Fig. 2 – Examples of characterized fault models (CFMs) with two large slip areas along the Nankai Trough. Super-large slip areas are additionally incorporated into the models on the far right-hand-side. The red, orange, and yellow colors denote the super-large slip area, large slip area, and background slip area, respectively. The grey lines indicate the hypothetical source areas defined by the Headquarters for Earthquake Research Promotion (HERP).

2.5 Sagami Trough

The Philippine Sea Plate and Pacific Plate subduct beneath the metropolitan area. The long-term evaluation by the HERP [7] categorizes the earthquakes along the plate boundary between the North America Plate and the Philippine Sea Plate as "M8-class earthquakes along the Sagami Trough". We modeled these earthquakes as specified fault models. The Genroku earthquake in 1703 and the Taisho Kanto earthquake in 1923 were included in this category. An Mw 8.6 earthquake with a rupture area of the entire region (as defined by the HERP) was the maximum size used in this study. The HERP [8] divided the hypothetical source area into five sub-regions, and we combined these sub-regions by adding two extra regions that correspond to i) the source area of the Genroku earthquake, and ii) the residual source area between the Genroku and Taisho earthquakes. We constructed approximately 100 specified fault models in total. Examples of specified fault models along the Sagami Trough are presented in Fig. 3.

As it is rather hard to specify the source area of M7-class earthquakes that are caused by the subducted plate along the Sagami trough [7], we modeled these earthquakes as unspecified fault models with large slip areas. These fault models were uniformly distributed within the hypothetical source area and the large slip areas were located at the center of the fault. The number of unspecified fault models used was approximately 900.

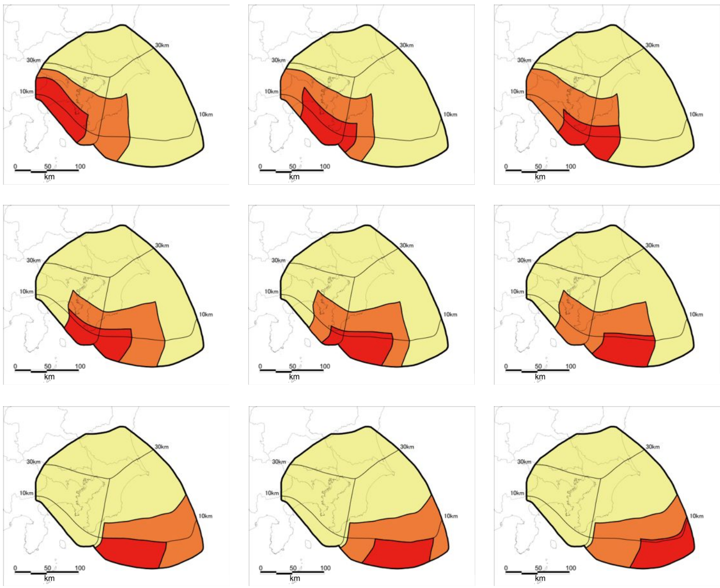

Fig. 3 – Examples of characterized fault models (CFMs) of Mw 8.6 along the Sagami Trough, whose rupture area extends to the entire region defined by the Headquarters for Earthquake Research Promotion (HERP). The red, orange, and yellow colors denote the super-large slip area, large slip area, and background slip area, respectively. The grey lines indicate the hypothetical source areas defined by the HERP.

3. Tsunami simulation

Prior to performing the tsunami simulations, bathymetry and topography data were prepared (see Fig. 4a, b). A nesting system that consisted of four different sized mesh data (1350 m, 450 m, 150 m, and 50 m) were constructed for the tsunami simulations (Fig. 4c, d). The entire region of the tsunami simulations was covered by the largest mesh data (1350 m), whereas coastal areas were covered by the smallest mesh data (50 m) because a high resolution is required to simulate tsunami propagation around coast areas.

Tsunami simulations were carried out as follows. First, the crustal deformation was calculated for each fault model using Okada’s formula [9] by accounting for the effect of horizontal deformation due to faulting [10]. Second, a Kajiura’s filter [11] was then applied to the crustal deformation to obtain the initial surface water displacement. Based on this initial surface water displacement, the tsunami propagation was computed by solving nonlinear longwave equations with advection and bottom friction terms using the finite-difference method, which included a run-up computation on land [12]. Once the tsunami simulation was complete, the maximum tsunami heights along the coast were extracted.

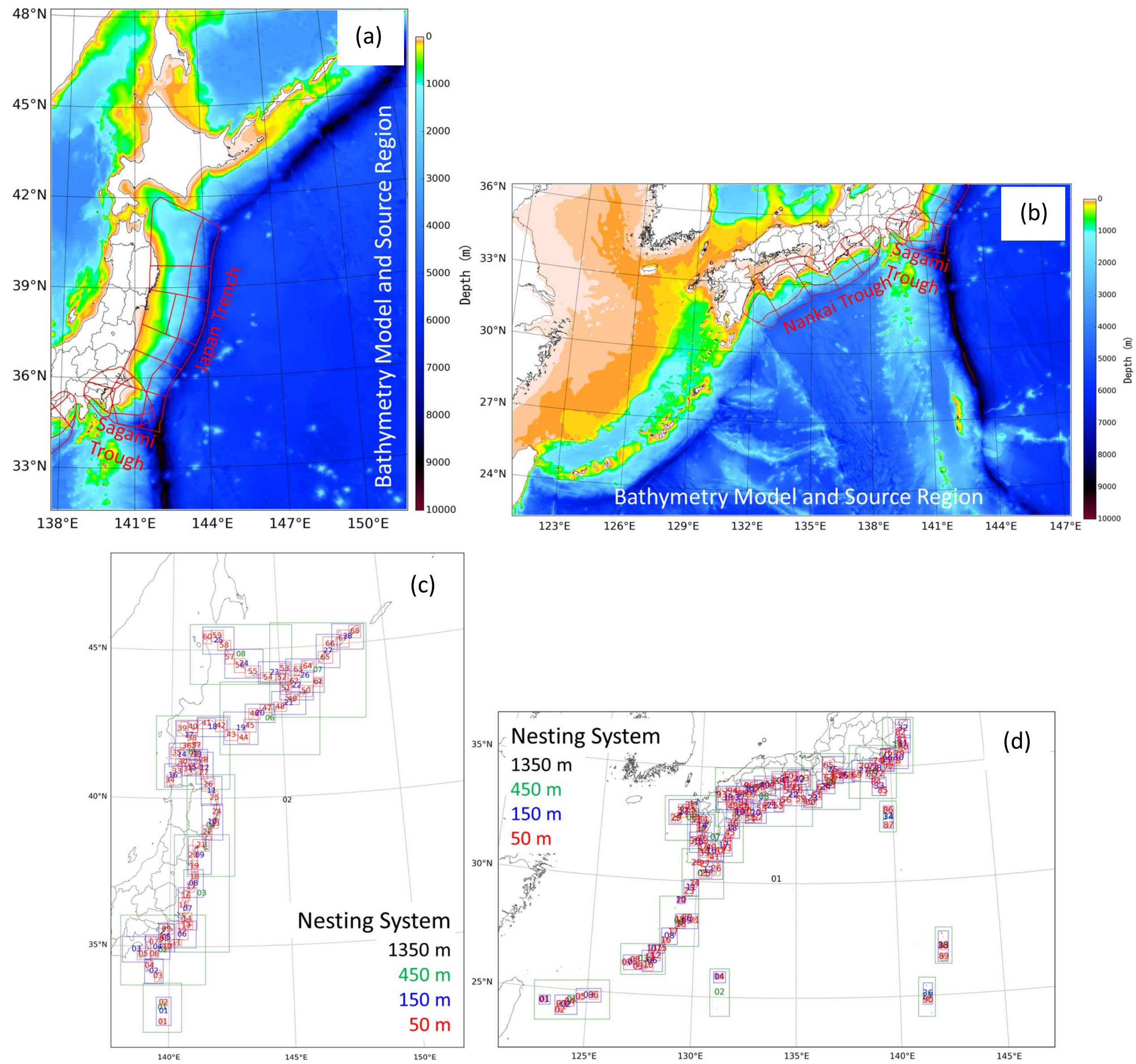

Fig. 4 – (a, b) Bathymetry models with hypothetical source areas defined by the Headquarters for Earthquake Research Promotion (HERP) (red lines). (c, d) The nesting system with 1350 m, 450 m, 150 m, and 50 m meshes used for the tsunami simulation.

Figure 5 displays the distribution of the simulated tsunami heights along the Pacific coast of Japan by using several thousands of CFMs set in the source regions along the Japan Trench, Nankai Trough, and Sagami Trough. It is noticeable that large tsunami heights appeared along the coast between Onagawa and Kuji and between Kashima and Sendai in the Japan Trench (see Fig. 5a), as well as along the coastal regions of Shikoku (region number 49-57) and the Kii Peninsula (region number 58-64) (see Fig. 5b), whereas tsunami heights along the Sagami Trough were relatively small (see Fig. 5c). The large tsunami heights were primarily the result of the super-large slip areas in the CFMs, and large tsunami heights therefore tended to appear along the coast in front of the super-large slip areas. Another crucial phenomenon to consider is the amplification of tsunamis near the coast. For instance, when observing the Sanriku region between Onagawa and Kuji in the Japan Trench, tsunamis may be amplified around the coast due to the so-called Rias coast, thus resulting in a large tsunami height.

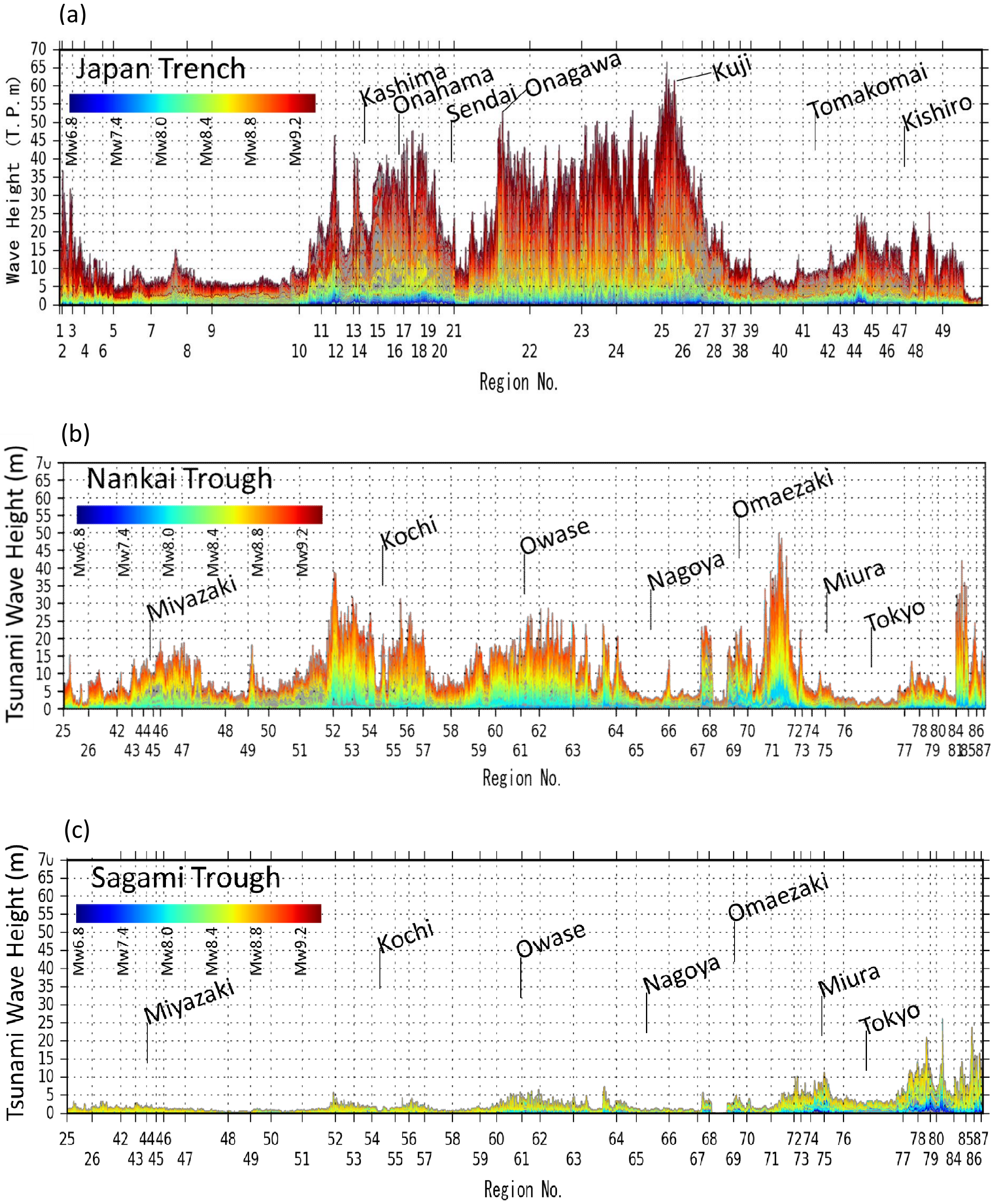

Fig. 5 – Distribution of tsunami heights along the coast in the (a) Japan Trench, (b) Nankai Trough, and (c) Sagami Trough. Colors denote the seismic moment magnitude (Mw). It can be seen that warm-colors (i.e., a large Mw) correspond to large tsunami heights and cool-colors (i.e., small Mw) to small tsunami heights.

4. Tsunami hazard analysis

A hazard analysis was carried out using the simulated tsunami heights along the coast of Japan. The probability of earthquake occurrence was determined based on the long-term evaluation by the HERP; thus, up-to-date scientific knowledge was incorporated into the PTHA. There are two kinds of probabilistic hazard models: the "present-time hazard model" and the "long-term average hazard model". In this study, we focused on the present-time hazard model with a base date of January 1, 2020. The probability of earthquake occurrence was estimated using the renewal process determined by the Brownian passage time (BPT) distribution for earthquakes whose parameters of the BTP distribution (e.g., the latest faulting time and average interval of earthquake occurrence) are evaluated by the HERP (i.e., Tohoku earthquake type, earthquake off northern Sanriku, and specified earthquake type along the Nankai and Sagami troughs). For the other earthquakes, whose parameters of the BTP distribution are not evaluated by the HERP (i.e., tsunami earthquake type and intraplate earthquake type), the probability of earthquake occurrence was estimated using a stationary Poisson process with an average occurrence frequency. For earthquakes whose average occurrence frequency is not evaluated by the HERP (i.e., the largest-class earthquake type, other interlocking earthquake type, and unspecified earthquake type along the Japan Trench and Sagami Trough), the average occurrence frequency was estimated by assuming a Gutenberg–Richter (GR) relationship with a b-value of 0.9 and an a-value that was estimated using the frequency-magnitude distribution obtained by the seismicity data in the target region.

When more than two source regions with different magnitude were set in one earthquake group, the probability of earthquake occurrence was distributed in terms of the magnitude according to the GR relationship with a b-vale of 0.9. When more than two CFMs with different slip patterns were set for one source region, the probability of earthquake occurrence was equally distributed. In spite of the aforementioned procedure for estimating the probability of earthquake occurrence, the probability of earthquake occurrence for the Nankai and Sagami troughs was, however, distributed using the relative probability, which was estimated based on the source region patterns of past earthquakes. Thus, probability models and the probability in 30 years from now for the hazard analysis were prepared and are shown in Table 1. Ten hazard assessment points were selected to calculate the hazard curve, as shown in Fig. 6. In Sections 4.1–4.3, the results of the tsunami hazard analysis using the parameters in Table 1 are presented for each region.

Table 1 – Earthquake groups with probability models and the probability in 30 years used for the tsunami hazard analysis

	Group name	Category	Mw	Probability model	Probablity in 30 years
Japan Trench	Tohoku earthquake type	specified	8.6–9.1	BPT distribution	0.0%
	earthquakes off northern Sanriku	specified	8.4–8.8	BPT distribution	19.1%
	tsunami earthquake type	specified	Mt9.0–8.6	Poisson Process	25.3%
	intraplate earthquake type	specified	8.2	Poisson Process	5.1%
	the largest-class earthquake type	unspecfied	9.0–9.4	Poisson Process	estimated by the GR relation
	other interlocking eathquake type ①		8.3–9.2		
	other interlocking eathquake type ②		8.2–8.9		
	unspecified earthquakes type		7.0–8.3		
Nankai Trough	specified earthquakes type	specified	8.3–9.2	BPT distribution	74.3%
Sagami Trough	specified earthquakes type	specified	7.9–8.6	BPT distribution	0.8%
	unspecified earthquakes type	unspecfied	6.8–7.8	Poisson Process	estimated by the GR relation

4.1 Tsunami hazard assessment along the Japan Trench

The 2011 earthquake off the Pacific coast of Tohoku (i.e., the great Tohoku earthquake) did not contribute to the hazard assessment because the earthquakes of the great Tohoku earthquake type currently have an occurrence probability of 0% in 30 years from now. For the earthquake groups of the interlocking earthquake type, the occurrence probability was estimated by the extrapolation of the GR model obtained by the seismicity data; however, these earthquakes are not evaluated by the HERP. These earthquake groups yielded hazard curve characteristics of a low probability and large tsunami height along the Japan Trench. The exceedance probability of 3m tsunami in 30 years is estimated to be more than 30 % along the wide range of the coast of the eastern Japan (from Ibaraki prefecture to Aomori prefecture).

4.2 Tsunami hazard assessment along the Nankai Trough

The Showa and Ansei earthquake group, in which the Nankai and Tonankai earthquakes occur separately, contributed to hazard curves that were characterized by a high probability and small tsunami height. On the other hand, the Hoei earthquake and the largest-class earthquake group, in which earthquakes in the Nankai and Tonankai regions occur simultaneously, contributed to hazard curves that were characterized by a low probability and large tsunami height. We constructed a large number of hazard curves along the Nankai Trough, and it was noticed that large hazard curves corresponded in particular to the coastal areas of Shikoku and the Kii Peninsula, where the exceedance probability of 3m tsunami in 30 years is estimated to be more than 30 %.

4.3 Tsunami hazard assessment along the Sagami Trough

Although the hazard curves were estimated to be relatively large in the Sotobo region and Izu-Ogasawara islands in comparison with other regions, the probability levels for the Sagami Trough tsunami were found to be more than one order of magnitude smaller than those of the Nankai Trough and Japan Trench tsunamis. This was because the M8-class earthquakes along the Sagami Trough currently have an occurrence probability of 0.8% in 30 years from now. The exceedance probability of 3m tsunami in 30 years is estimated to be more than 0.1 % in the Sotobo region and Sagami bay, and less than 0.1 % in other regions.

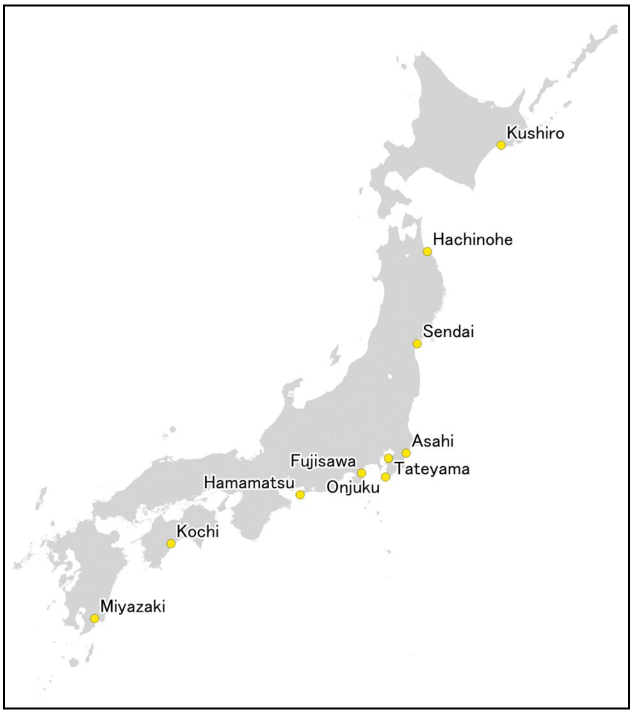

Fig. 6 – Map showing the hazard assessment points (yellow dots) for the hazard curves in Fig. 7.

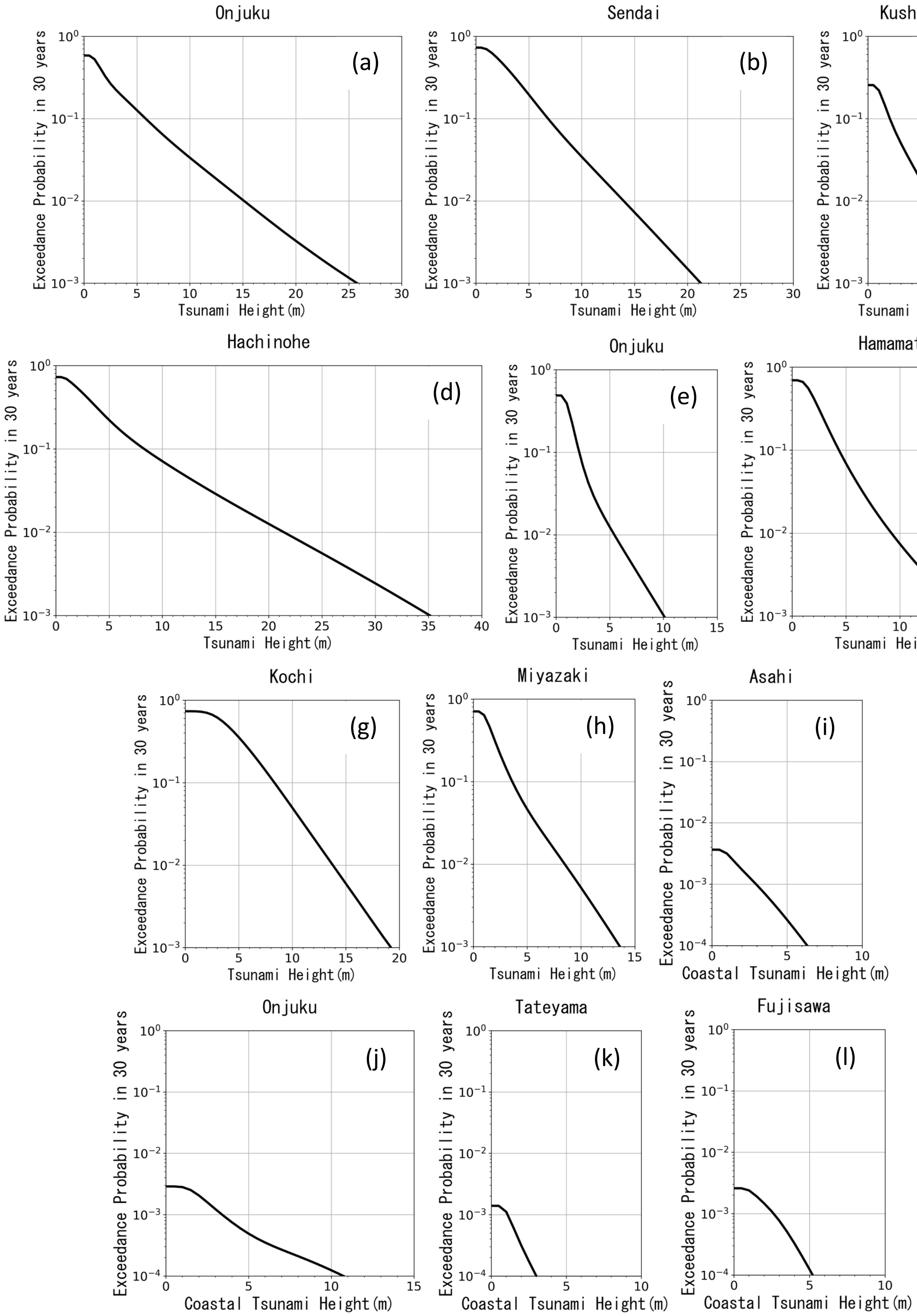

Fig. 7 – Tsunami hazard curves calculated at hazard assessment points (see Fig. 6) along the Japan Trench (a–d), Nankai Trough (e–h), and Sagami Trough (i–l). The vertical and horizontal axes denote the exceedance probability in 30 years and the tsunami height, respectively.

5. Conclusion

We conducted a PTHA along the Japan Trench, Nankai Trough, and Sagami Trough based on the occurrence probability of the long-term evaluation by the HERP and tsunami simulations. The exceedance probability in 30 years from now at the representative points was found to be high along the Japan Trench and Nankai Trough but relatively small along the Sagami Trough. We are planning to work on PTHAs for other sea areas to obtain a comprehensive PTHA for Japan in the foreseeable future.

6. Acknowledgements

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