Executive Summary

This report is a summary of the process and results of applying the Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 for the first time in Japan with regard to a probabilistic seismic hazard analysis (PSHA) of the Ikata Nuclear Power Plant (Ikata Site), operated by the Shikoku Electric Power Company (referred to as Yonden, based on the Japanese name).

1. Project Objectives and Scope

Deterministic evaluations based on regulatory requirements and the factors needed in the uncertainty of future earthquakes are essential for design-basis earthquake ground motion, Ss, used in seismic motion safety evaluations of nuclear power plants in Japan. Meanwhile, electric power companies are also implementing PSHA for evaluations of regulatory requirements because of the need to refer to the exceedance probability of the deterministically evaluated design-basis earthquake ground motion Ss as a factor in the validity evaluation of the determined Ss.

To reduce risks associated with rare external events, such as earthquakes and tsunamis, and particularly in response to the 2011 Tokyo Electric Power Company (at the time) Fukushima Daiichi Nuclear Power Plant accident in 2011, probabilistic risk assessment (PRA) and risk-informed decision making (RIDM) were identified to be established. In October 2014, the Nuclear Risk Research Center (NRRC) was established within the Central Research Institute of Electric Power Industry to develop the methodologies of PRA and to support utilities' RIDM.

Yonden and NRRC recognized the need for enhancement of PSHA because it is a prerequisite for increased sophistication of seismic PRA. They thus decided to implement a SSHAC Level 3 PSHA approach at the Ikata site. The approach has often been implemented internationally to address regulatory requirements but this is the first time in Japan.

As described above, several PSHAs based on international SSHAC Level 3, including those in the United States, have been implemented to address regulatory requirements. However, the SSHAC Level 3 Project at the Ikata site ("Ikata SSHAC Project") is a voluntary study by Yonden for the purpose of further improving safety by enhancing PSHA. The results of this study are not limited to the Ikata site and may significantly contribute to the widespread enhancement of PSHAs in Japan.

The goal of the Ikata SSHAC Project is to implement PSHA based on SSHAC Level 3 and construct a technologically justified probabilistic seismic hazard curve ("hazard curve") and associated uncertainties ("hazard distribution"), which contribute to the seismic PRA of the Ikata site.

Detailed specifications of the study are as follows:

- The evaluation point is set as the core of Ikata Nuclear Power Plant 3 (33.491° N, 132.311° E), and the ground motion is set as Vs = 2.6 km/s on a free rock surface (EL. + 10.0 m).
- The period for calculating the earthquake occurrence probability is set as 50 years with the starting point of the calculation set on January 1, 2019, based on the service period of the Ikata site.
- The target period is set as 0.02–5 s, considering the characteristics of the facilities that are subject to PRA.

- The hazard curve is established based on the acceleration response spectrum (damping ratio: 5%) and will be accurate for the response acceleration level that influences the seismic PRA.
- The output of PSHA is set as the hazard curves (horizontal, vertical) for each period (0.02 s, 0.09 s, 0.13 s, 0.25 s, 0.60 s, 1.00 s, 2.00 s, and 5.00 s) and the uniform hazard response spectrum (horizontal, vertical).
- A response analysis is conducted using input ground motion based on hazard curves defined by the free surface of the base stratum in realistic response analysis of building and equipment fragility assessments. However, this uncertainty associated with the setup of the spectral shape of the input ground motion is considered during fragility assessment; therefore, the uncertainty evaluation of response analysis is not needed in this SSHAC project.

As mentioned above, this project is based on the engineering objective of enhancing the PSHA, which contributes to the seismic PRA of the Ikata site. Therefore, TI teams(which will be described later) created rankings to prioritize the factors (e.g., earthquakes and seismic motion evaluation methods) with a high degree of influence on the hazard curve and sought to obtain valid results by effectively applying limited resources throughout the study process.

Additionally, there were cases where the sensitivity analysis and prioritized orders of other recognized factors were different from what was expected depending on the progress of the study process. Accordingly, TI teams implemented suitable studies with the appropriate priorities assigned.

As mentioned above, this project is a site-specific PSHA study that was implemented as a review process for conducting a seismic PRA at the Ikata site. The study was conducted according to the procedures stipulated by the SSHAC Level 3 guidelines.

1.1 Organizational Structure / Procedure: SSHAC Level 3

This project was undertaken in accordance with the following U.S. guidelines pertaining to SSHAC Level 3 ("SSHAC guidelines").

- NUREG/CR-6372, Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts
- NUREG-2117, Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies
- NUREG-2213, Updated Implementation Guidelines for SSHAC Hazard Studies

NUREG-2213 cites the following five items as necessary factors for SSHAC.

- All participants are given a clearly defined role.
- An objective assessment of all available data, models, and methods relating to PSHA is conducted.
- A model is built by integration based on an optimal assessment of current information and associated uncertainties. The model is to accurately express the center, body, and range of technically defensible interpretation (CBR of TDI).
- The study contents should be documented with sufficient accuracy.

- The study should be reviewed by an independent participatory peer review panel (PPRP).

The above requirements were carefully observed and implemented in this project.

The uncertainty of future earthquakes in this study can be broadly classified as aleatory variability due to the randomness of natural phenomena and epistemic uncertainty due to insufficient knowledge. The former can be modeled as a probability distribution, whereas the latter can only be assessed based on expert judgment and is expressed with a logic tree that systematically aggregates expert opinion. The SSHAC guidelines strictly formulate procedures for suitably processing this type of uncertainty, particularly fulfilling an important deterministic role in the evaluation of epistemic uncertainty.

This project was further developed considering the following three points based on the SSHAC guidelines.

(1) Clarify the CBR of TDI in the associated fields of seismology, geology, and seismic engineering associated with PSHA.

(2) Technical studies should be implemented not individually, but as a part of technical integrator (TI) teams. TI teams comprise researchers and technicians with sufficient expert knowledge and the ability to discuss from a broad perspective, and discussions are to be directly held as a general rule. Discussions of the TI team are to be advanced under the responsibility of the TI Lead, and the TI team is responsible for the contents of the discussions and its results.

(3) Workshops are held, and the specific progress status of the project is to be published at each stage of the discussion. These results are to be reflected in the implementation of the project through an exchange of opinions with external experts, for example, by requesting differing opinions from associated fields.

The frameworks (1), (2), and (3) ensure the “defensibility” “quality,” and “transparency” of the project, respectively.

Furthermore, this project is the first SSHAC Level 3 Project in Japan. Considering that there are no prior associates of an SSHAC Level 3 project in Japan, NRRC that manages this project requested the participation of the US experts who are familiar with SSHAC to satisfy the procedure, content, and quality of this study according to the SSHAC Level 3 standards, in addition to Japanese experts who are familiar with seismic sources specific to the Ikata site.

The resulting organizational structure of this project is shown in Fig. 1. In this system, all technical decision responsibilities relating to the construction of the hazard-input models are with the TI team, and the project sponsor, Yonden, cannot influence this interpretation.

With regard to experts on the U.S. implementation of SSHAC procedures, NRRC Director George Apostolakis (previously one of the authors of NUREG/CR-6372) as well as Kevin Coppersmith, who is one of the authors of NUREG/CR-6372, NUREG-2117, and NUREG-2213 and has extensive past experience in several SSHAC Level 3 projects, participated in the project as advisers. Similarly, Martin McCann Jr., who also has past experience in SSHAC Level 3 projects, participated as a PPRP member.

PSHA inputs require the modeling of seismic source characterization (SSC) and ground motion characterization (GMC). The position, scale, and activity intervals of all the seismic sources to be considered need to be examined in the SSC model, whereas the evaluation method of the ground motion, propagation process, and amplification characteristics of the site must be examined in the GMC model.

The SSHAC guidelines clearly define the roles and responsibilities of associates involved in the project, and all technical reviews will be conducted by the TI team.

It was decided in this project that each TI team (SSC and GMC TI teams) would be set up according to previous SSHAC Level 3 projects and previously mentioned SSHAC guidelines for advancing each study for the SSC and GMC models. Furthermore, a PPRP, hazard analyst (HA), database manager (DM), resource expert (RE), and proponent expert (PE) were selected according to SSHAC guidelines.

The study procedure of this project based on SSHAC guidelines is as shown in Fig. 2, with the study divided into three stages.

The first stage is “Evaluation,” where the TI team evaluates the quality and reliability of the data, methods, and models that can be used for PSHA, particularly focusing on applicability to the specified site. Accordingly, the TI team invites external experts, referred to as resource experts (RE), at Workshop #1 to explain usable data and methods regarding hazard significant issues (HSI) relating to PSHA. In addition, the TI team invites external experts referred to as proponent experts (PE) at Workshop #2 to explain and advocate specific models, thereby conducting direct discussions between the TI team and PEs at this workshop.

During the "Integration" stage, which follows "Evaluation," the TI teams build their SSC and GMC models that includes logic trees that capture their state of knowledge and uncertainty and thereby achieve the CBR of TDI, which is the basic concept of SSHAC. During this study stage, preliminary SSC and GMC models are first created, and a hazard analysis is conducted with the applicable models. These results (particularly the sensitivity analysis results) and the comments relating to the preliminary model from the PPRP are used as feedback at Workshop #3 to create a subsequent final model.

The study contents of the final model must be accurately documented in the final "Documentation" stage.

All the aforementioned study processes are reviewed by the PPRP. The PPRP review focuses on two aspects: technical perspectives (i.e., whether the model created by the TI team appropriately captures the CBR of TDI) and the implementation of the SSHAC study procedure.

The study of interactions between the SSC and GMC TI teams (i.e., role division and collaboration methods) were particularly considered in this study. In other words, not all studies can be divided between the SSC and GMC TI teams, and mutual discussion between the two teams regarding studies at the interface are crucial. Therefore, a forum for discussion and sharing of mutual recognition was set up between the SSC and GMC TI teams throughout the study process.

This project was undertaken from March 2016 to September 2020. The

Kickoff Meeting, Workshops #1–3, and Working Meetings #1–5 were held in Tokyo.

At Workshop #1, the TI Team identified the HSI and REs reported on the associated data, methods, and models. At Workshop #2, the PEs discussed alternative models for the various factors of importance and discussed with the TI team. At Workshop #3, the hazard analysis results including various sensitivity analysis results based on the preliminary models created by the TI teams were explained, and the PPRP provided feedback. Discussions and studies that complemented these workshops were held at the Working Meetings, which were held five times each, i.e., 10 times in total, by the SSC and GMC TI teams.

All TI team members, the PPRP, and the adviser, Dr. Coppersmith, participated in the workshops, and regulatory officials and electric power company associates also attended. Working meetings were held by the SSC and GMC TI teams. All applicable TI team members, a PPRP representative, and an expert with experience in SSHAC Level 3 projects (i.e., either Prof. McCann from PPRP or the adviser, Dr. Coppersmith) always participated, and similar to the Workshops, a regulatory official was in attendance.

Furthermore, preliminary TI team meetings were held for daily discussions within the TI team as the study progressed. A forum where the PPRP and TI teams can discuss was set up, considering that this project was the first SSHAC Level 3 project in Japan.

This project fundamentally followed the SSHAC guidelines considering the aforementioned study system and procedure. However, there are some aspects of the system that differ from those of international SSHAC Level

3 projects. In this project, the TI team primarily composed of university or research institution associates in accordance with existing evaluations in Japan (e.g., evaluations by the council of the Headquarters for Earthquake Research Promotion (HERP)). However, there were certain limits in terms of the time and work that each organization could contribute to a single private project. Therefore, as a part of the TI team, “TI support team” was set up in this project to maintain basic materials and prepare discussion materials. Despite the considerable assistance provided by the TI support team, all decisions were made by the TI teams, even under this system.

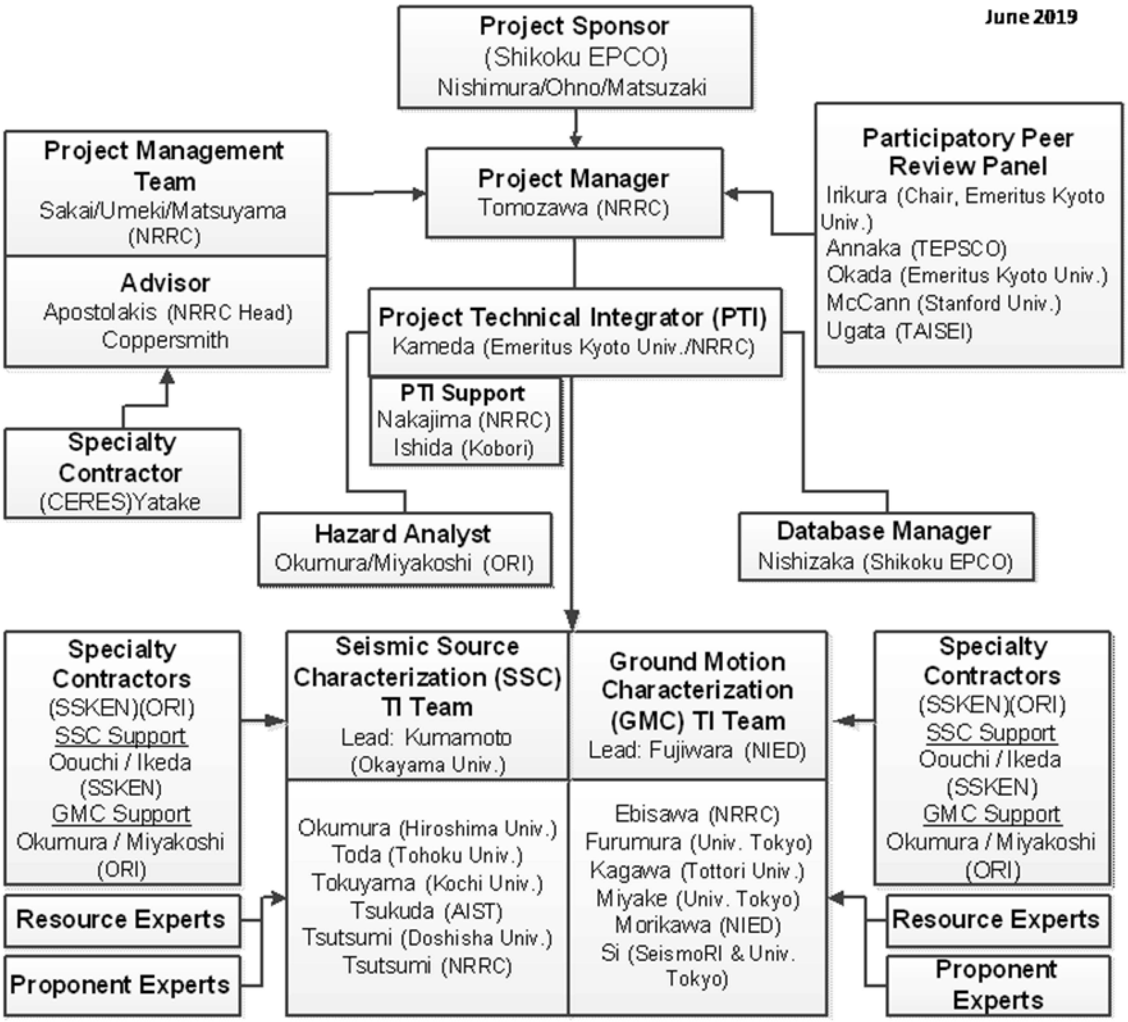

Fig. 1 Organizational structure

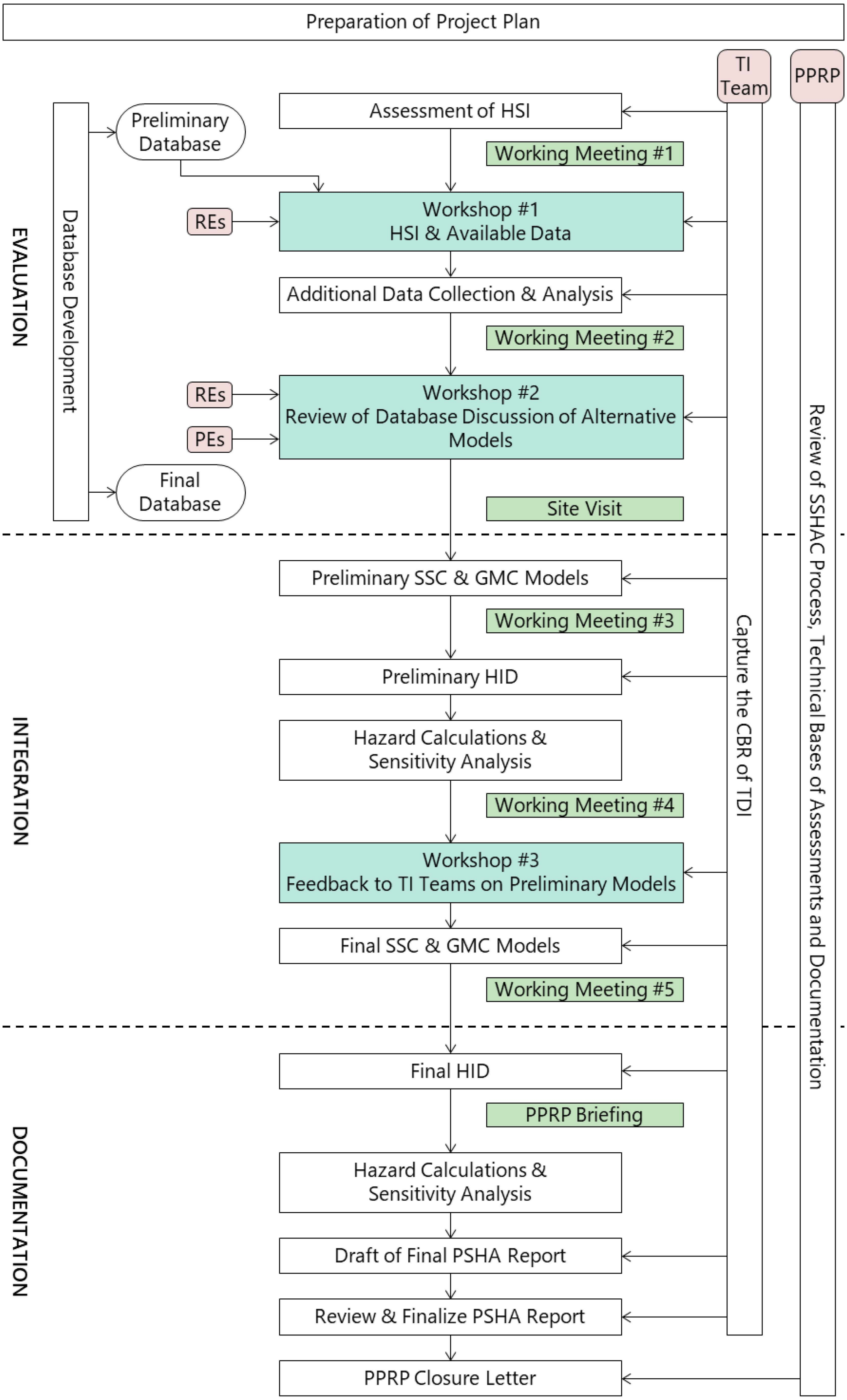

Fig. 2 Project study procedure

1.2 Earthquake Environment of Ikata Site

The Ikata site is located in Ikata-cho, Ehime Prefecture, in western Shikoku (Fig. 3). The seismic tectonics around the Ikata site are characterized by the Philippine Sea Plate subducting from the southern Nankai Trough and median tectonic line (MTL) active fault zone (MTLAFZ), which is the central fault of the island arc. The Ikata site is located on the front arc sliver of the southern side of the MTLAFZ. A conceptual diagram of seismic tectonics around the Ikata site and cross-sections that are orthogonal to the MTLAFZ is shown in Fig. 4. The Ikata site is located at the northern limit of the predicted seismic source of the “Nankai Trough Megathrust Earthquake,” and the activity of a “blind earthquake in the Philippine Sea Plate," which deepens in the northwestern direction along the subducting Philippine Sea Plate, can be observed at its depths. Moreover, there is an east-northeast–west-southwest striking right-lateral strike-slip MTLAFZ and a right-lateral active fault running parallel to this. Furthermore, “MTLAFZ earthquakes” and “miscellaneous active intraplate fault earthquakes” (including “earthquakes smaller than the characteristic scale of active intraplate faults”) caused by active intraplate faults and “blind earthquakes of landward plates” in areas where active faults are unspecified occur in the shallower seismogenic layers.

The geology of southwestern Japan in the Japanese archipelago has zones that are divided between the northern inner zone and southern outer zone with MTL as the boundary in the island arc direction. The inner zone on the northern side of the site is in the Ryoke belt, which includes Ryoke metamorphic rocks subjected to high-temperature or low-pressure metamorphism, as well as Ryoke granitoids, Hiroshima granitoids, and the Izumi Group. Additionally, the outer zone geology near the site is divided between the Sambagawa belt, Chichibu belt (northern, central, and southern Chichibu belts), and Shimanto belt from the north, depending on the age and lithology. Basic schists belonging to the Sambagawa belt are widely distributed in the Sadamisaki Peninsula, where the Ikata site is located.

The PS-logging results which was conducted up to 2000m in depth at the Ikata site showed extremely high velocities exceeding Vs = 2 km/s and 3 km/s in the shallow(up to a depth of several 100m) and deep underground (several 100m deeper)sections, respectively, which gradually increased in the depth direction. Detailed survey results did not reveal any underground structure that may cause ground motion amplifications at the Ikata site, and seismic observation records collected since 1975 did not show the occurrence of any peculiar ground amplification.

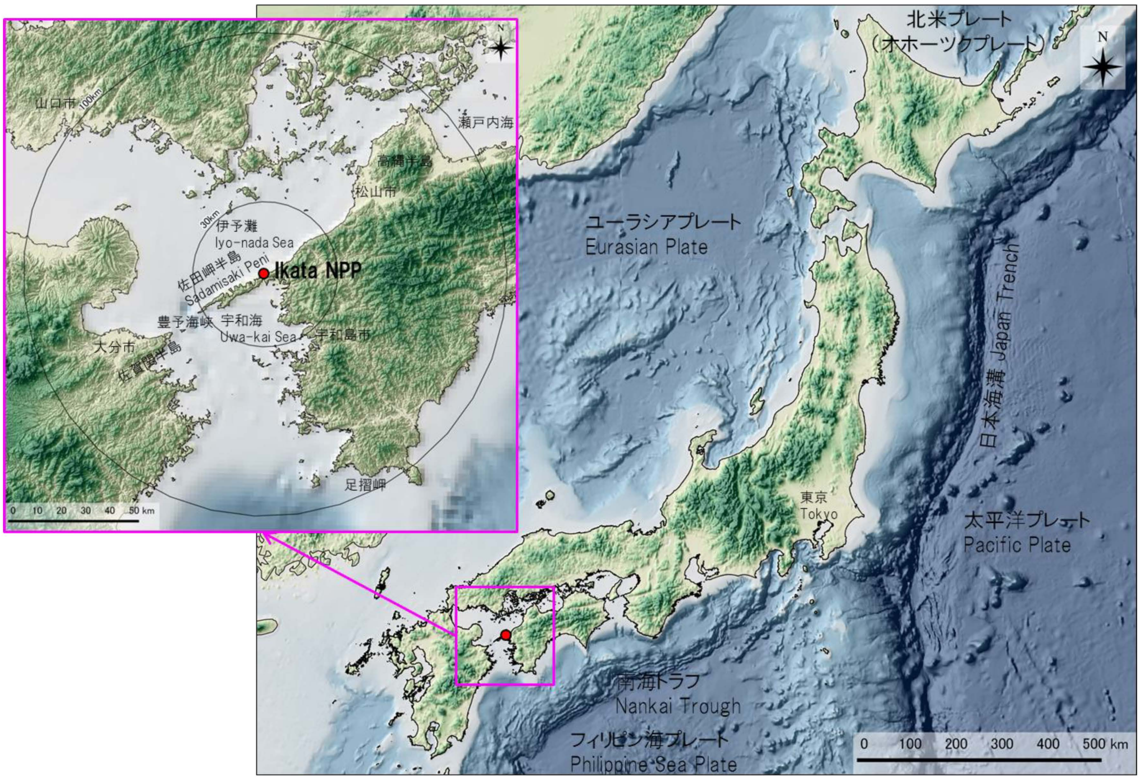

Fig. 3 Location of the Ikata site

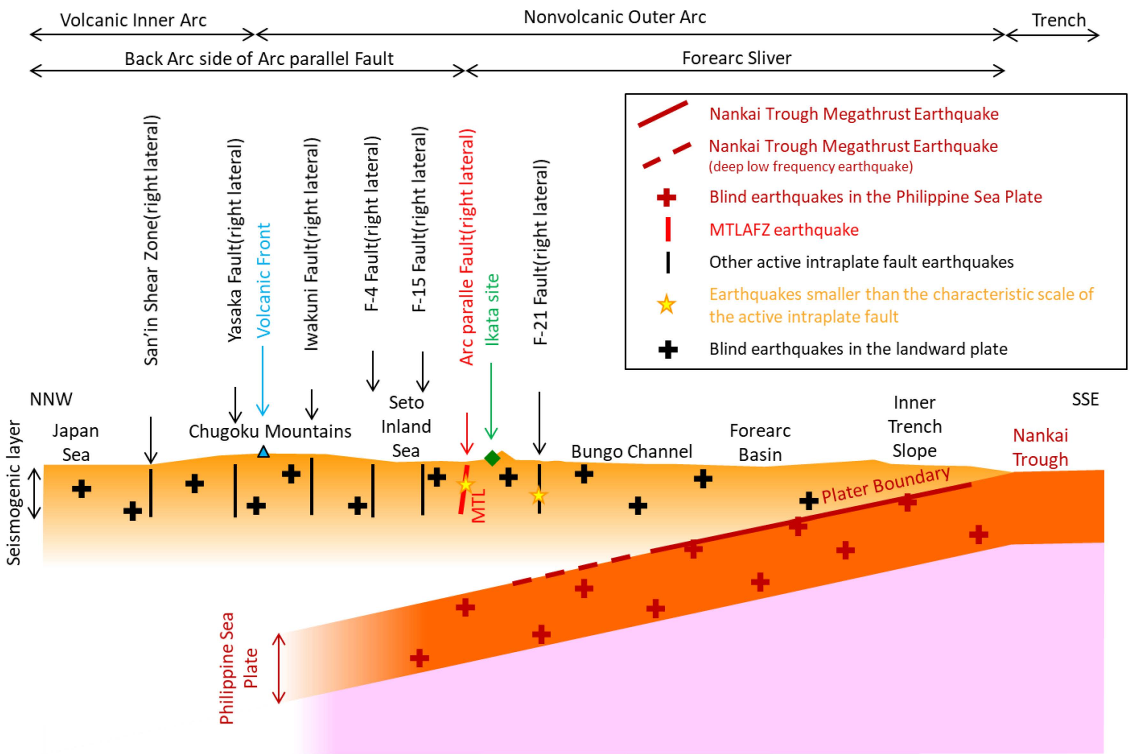

Fig. 4 Conceptual diagram of seismic tectonics around the Ikata site

(MTL cross-section)

2. Technical Basis for PSHA

The technical basis for PSHA of the Ikata site was formed according to the SSHAC Level 3 processes based on “Evaluation” and “Integration”. Data, models, and methods identified and recognized by the technical community (e.g., academic societies) were specified, analyzed, and evaluated in the “Evaluation” stage. The TI team constructed SSC and GMC models, which express the CBR of TDI in the “Integration” stage.

Academic publications and survey results related to the hazard significant issues (HSI) of SSC and GMC models and earthquake catalogs were analyzed and evaluated at the “Evaluation” stage. These processes were actively implemented alongside data provisioning from the RE at Workshop #1. Further discussions on additional data, models, and methods were held at Workshop #2 as the study progressed.

The handling of evaluation results by public institutions in Japan, such as HERP, is considered as one of the vital processes pertaining to the "Evaluation" stage. However, the evaluation process by such public institutions is not based on SSHAC Level 3 studies; therefore, it is inappropriate to directly adopt the applicable results, and validity assessments based on the original data are necessary.

2.1 SSC Data

The purpose of constructing a database is to collect references relating to PSHA for this project, to share them with project associates (including the TI team), and to use them as the objective basis for PSHA. Progress was made on the construction of the database from the initial stages of the project to promote efficient discussion and work in the TI team, and data were collected until the construction of the final model.

The SSC database was constructed in a tabular format, in which a data evaluation table (DET) was added to a literature source list, referring from NUREG-2117. The literature includes previous applications for permission to change installations at the Ikata site; public documents and survey materials used in PSHA; foreign or domestic data on geography, geology, earthquakes, and PSHA around the Ikata site; documents useful for collecting, organizing, and creating models; and the PSHA of a wide range of international SSHAC Level 3 project case studies. Moreover, data discussed at workshops for this project (i.e., RE-/PE-published documents or referenced literature) were registered and included in the project database.

An earthquake catalog is extremely important in PSHA as data on seismic activity. In Japan, there are historical earthquake catalogues which include damage data after about 500 AD. Japan Meteorological Agency (JMA)-unified M ≥ 1.0 earthquakes that occurred from October 1, 1997 to May 31, 2016 were de-clustered using methods by Reasenberg (1985) and used for the “Ikata SSHAC catalog” set as the seismic source data used in the analysis for this project, based on the following three conditions: (1) long-term records are present, (2) comprehensive records are provided (i.e., excellent detection accuracy), and (3) transient earthquakes are excluded.

Detailed yet wide-ranging data on (a) location (position or shape), (b) magnitude, and (c) occurrence probability were collected in this project to construct an SSC model of the following six types of earthquakes subject to investigation.

(1) Nankai Trough Megathrust Earthquake

(2) Blind earthquakes in the Philippine Sea Plate

(3) MTLAFZ earthquakes.

(4) Other active intraplate fault earthquakes

(5) Earthquakes smaller than the characteristic scale of active intraplate faults

(6) Blind earthquakes in landward plates

Notably, a significant amount of data has been accumulated at the Ikata site owing to voluntary research activities conducted by the project sponsor, Yonden, over long durations. Consequently, TI teams were able to conduct a study that incorporated the latest data from the outset of the project, thereby avoiding the need for additional investigations to be conducted during this project.

2.2 GMC Data

The study items for the construction of a database for GMC in this project are as follows: 1) creation of a ground motion database, 2) selection of a ground motion prediction equation (GMPE) applicable to the site and correction of site characteristics, and 3) validity evaluation of applying the fault rupture model.

2.2.1. Creation of Ground Motion Database

As previously mentioned, seismic observations at the Ikata site began in 1975, and there have been 57 earthquakes with a maximum acceleration of over 2 cm/s^2 by December 2016. Most of these earthquakes occurred in the interior of the Philippine Sea Plate; few crustal earthquakes occurred during the period of observation. The maximum observed acceleration (horizontal) of the ground motion is approximately 90 cm/s^2.

Ground motion records from the National Research Institute for Earth Science and Disaster Resilience (K-NET, KiK-net), JMA, and the Port and Airport Research Institute, in addition to those at the Ikata site, were used as a ground motion database for this project.

2.2.2. Selection of GMPE Applicable to Site and Correction of Site Characteristics

When selecting a GMPE that is applicable to the Ikata site, the GMC TI team clearly defined the extraction conditions and selected numerous domestic and international GMPE candidates. The extraction conditions include the ability to evaluate according to the period range (0.02–5.0 s) and earthquake type and the ability for near-distance earthquake applications. Applicability to the M9 class was also considered as a reference condition.

The ground at the Ikata site is extremely hard rock with Vs=2.6 km/s; therefore, a site correction was conducted for the selected GMPE, and a final GMC model was constructed. Notably, for site correction, as minimal ground motion was observed at the Ikata site, observation points published by seismic observation records (National Research Institute for Earth Science and Disaster Resilience (K-NET, KiK-net), JMA, and the

Port and Airport Research Institute) were set as study subjects in addition to seismic observation data at the Ikata site.

2.2.3. Evaluations of the Fault Model

A major study factor relating to the GMC model in this project included the application of a characterized seismic source as a ground motion evaluation, which used fault model simulations on the PSHA ("fault model"). The primary reason for the introduction of the fault model in this project was due to the presence of MTLAFZ near the Ikata site and the absence of ground motion recordings at short distances. When applying the fault model to the PSHA, Dr. Norm Abrahamson was invited as a PE in Workshop #2 to report case studies of fault models in the United States, conduct comparisons and analyses with existing study methods, and study epistemic uncertainties on the median values of ground motion prediction and variations in ground motion near the seismic source.

The uncertainties to be evaluated with logic trees in these investigations were quantified using methods based on a characterized seismic source model, which used the "strong ground motion prediction method for earthquakes with specified source faults ('recipe')" established by HERP, and the six types of methods indicated by the Southern California Earthquake Center (SCEC) Broadband Platform (BBP) in the United States.

3. SSC Model

The SSC model is employed in PSHA to evaluate the location, size, and activity of the seismic source. Source parameters in the SSC model of this project were modeled separately for each of the previously mentioned seismic sources.

The positional relationship between the Ikata site and the Philippine Sea Plate is shown in Fig. 5. The Ikata site is located in the northern limit of the predicted source area of the Nankai Trough Megathrust Earthquake as the Philippine Sea Plate subducts to the northwest. The earthquakes that repeatedly occur in the Nankai Trough and others that occur in the Philippine Sea Plate were modeled as the "Nankai Trough Megathrust Earthquake" and "Blind earthquakes in the Philippine Sea Plate," respectively.

The active fault distribution around the Ikata site is shown in Fig. 6. The Ikata site is located on the southern side of the MTLAFZ, which is the central fault of the right-lateral strike-slip island arc related to oblique subduction of the Philippine Sea Plate. In this project, earthquakes that occur in the intraplate crust were modeled as "MTLAFZ earthquakes," the Gotanda and F-21 faults as "other active intraplate fault earthquakes," and "earthquakes smaller than the characteristic scale of the active intraplate fault," respectively, and that in areas with unknown active intraplate faults as "blind earthquakes in the landward plate."

An overview of the modeling is shown below.

The most important concept in SSHAC guidelines is to construct a model that captures the CBR of TDI for uncertainty assessments.

When setting branches in the SSC model, a corresponding number of branches were set up in cases where a bimodal or trimodal uncertainty distribution was shown. In cases where there was a range among designated assessments set in a single branch, the center of that range was generally used to conduct a fair and valid PSHA. Furthermore, weights of the SSC model were determined based on the presence and reliability of direct and indirect data relating to expert assessments and were expressed using the center, body, and range at the edges.

The (a) location (position or shape), (b) magnitude, and (c) occurrence probability (Table 1) were set up based on these basic ideas, thereby setting the logic tree branches and weights. The sensitivity analysis results revealed that earthquakes smaller than the characteristic magnitude had virtually no effect on earthquake hazards, except earthquakes that occur in the Iyo-nada Sea segment in the MTLAFZ closest to the Ikata site; therefore, only earthquakes smaller than the characteristic magnitude that occurred at the Iyo-nada Sea segment were considered.

A logic tree relating to the scale of the MTLAFZ earthquakes is shown as an example of a logic tree for the SSC model in Fig. 7. Note that the MTLAFZ is reviewed on the basis of historical earthquakes based on ancient documents, activity history from paleo-earthquake surveys, geometrical forms, such as the step width of active faults, and data on lateral displacement velocity and geological structure. They are divided into eight segments considering their interlocking behavior.

Table 1 Primary models according to earthquake type and evaluation item for study around the Ikata site

Earthquake type – Main model for each evaluation item		(a) Location (position/ shape)	(b) Scale(Magnitude)	(c) Occurrence probability
(1)	Nankai Trough Megathrust Earthquake	- predicted source area - Upper / lower end of the fault plane	- Calculation of earthquake scale - Earthquake scale prediction equation	- Average activity interval - Latest active period - Variation in activity interval - Probability model - Linkage evaluation methods
(2)	Blind earthquakes in the Philippine Sea Plate	- Setup of area classifications - Plate shape - Ratio of inter- and intra-plate earthquakes - Fault plane (position / shape)	- Maximum scale of intra- and inter-plate earthquakes	- Earthquake catalog - G-R law calculation - Probability model
(3)	MTLAFZ earthquake	- Plane position - Segment classification - Depth of the upper / lower end of the fault fracture area and source fault - Fault inclination angle	- Scale evaluation methods during interlocking - Parameters used in earthquake scale calculation (fault length / fault surface area) - Earthquake scale prediction equation	- Average activity interval evaluation method - Latest active period - Variation in activity interval - Average displacement velocity - Amount of displacement per round - Probability model - Linkage evaluation methods
(4)	Other active intraplate fault earthquakes	- Subject active fault - Presence of active fault - Depth of the upper / lower end of the fault fracture area and source fault	- Setup of earthquake scale - Earthquake scale prediction equation (setup of fault surface area) - Inclination angle	- Average activity interval - Calculation method of average active fault interval - Latest active period - Variation in activity interval - Probability model
(5)	Earthquakes smaller than the characteristic scale of the active intraplate fault	- Fault plane (position / shape)	- Maximum scale	- Occurrence frequency - Probability model
(6)	Blind earthquakes in the landward plate	- Setup of area classifications - Upper / lower end of seismogenic layer - Fault plane (position / shape)	- Maximum scale	- Earthquake catalog - G-R law calculation - Probability model

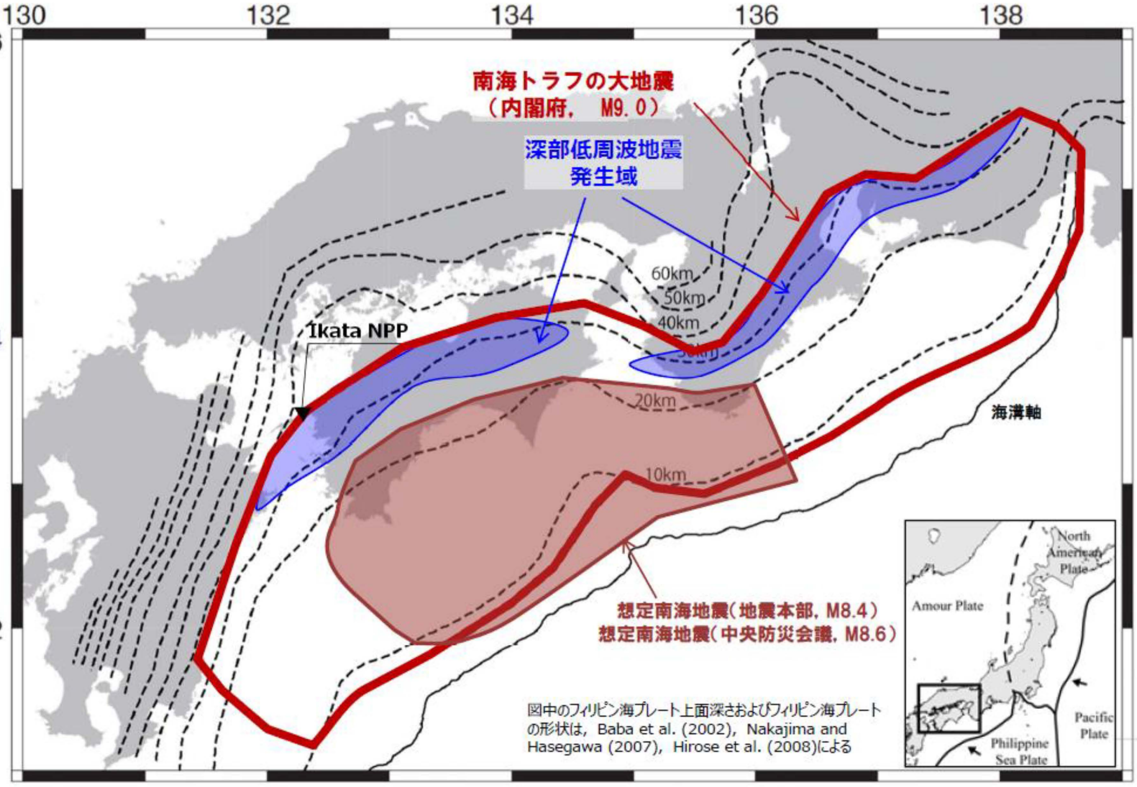

Fig. 5　Positional relationship of Ikata site and Philippine Sea Plate

Area of red solid line: Source area of M9 earthquake (Cabinet Office Evaluation)

Red shaded area: Source area of M8.4-8.6 earthquake (HERP)

Blue shaded area: Deep low frequency earthquake occurrence area

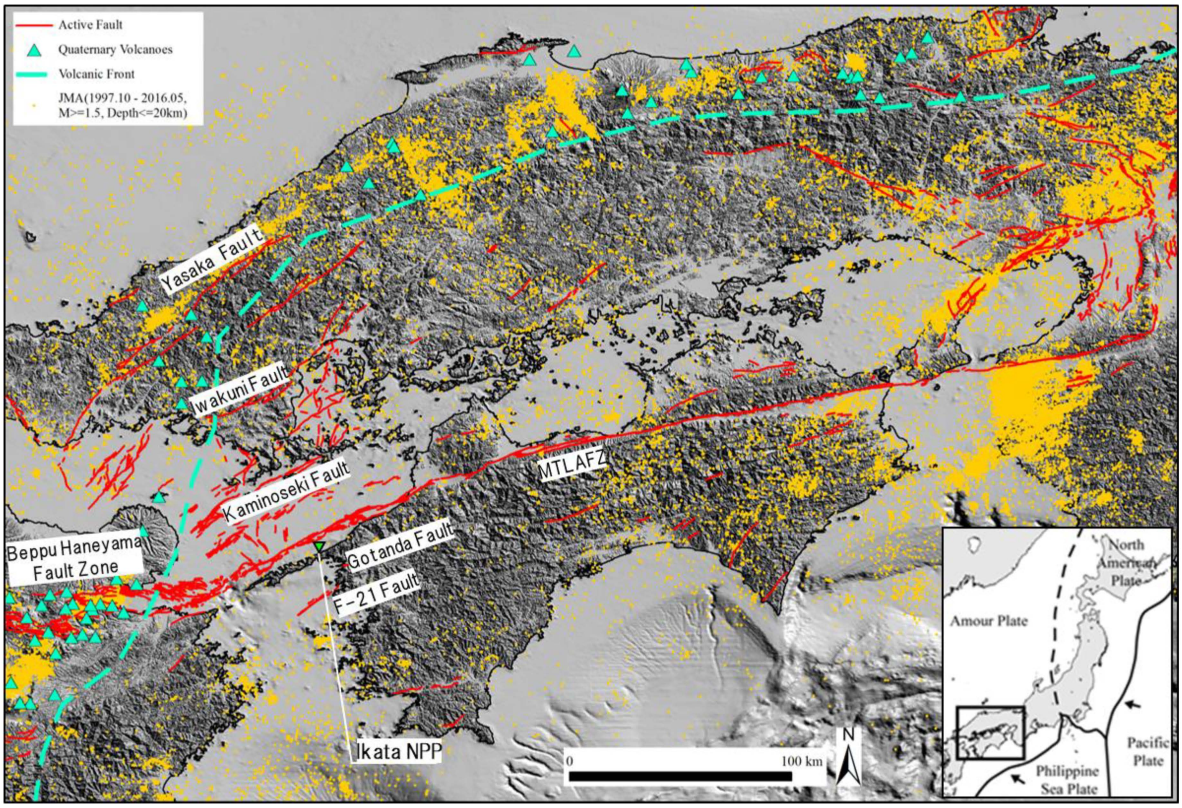

Fig. 6 Active fault distribution around Ikata site

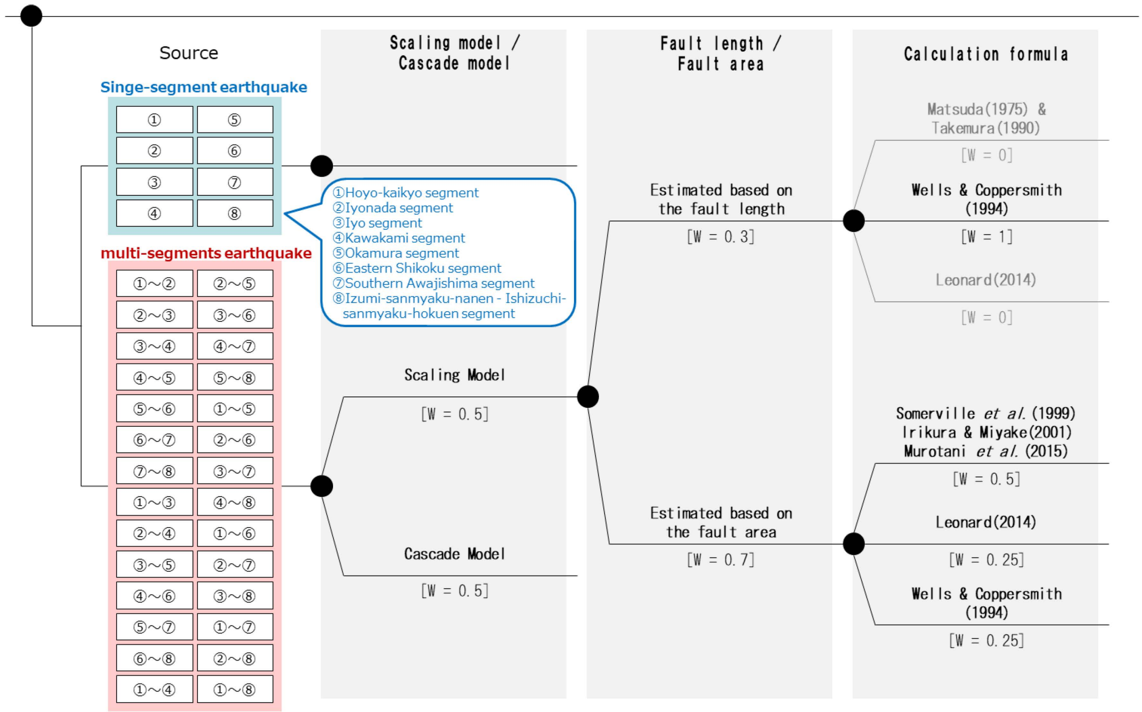

Fig. 7 Example of logic tree for SSC model (scale of MTLAFZ)

4. GMC Model

The GMC model is employed in PSHA to evaluate the ground motion from each seismic source. The GMC model for this project was developed for each seismic source (each earthquake type category) as follows:

- Ground motion evaluation method (GMPE, fault model)
- GMPE (when the ground motion evaluation method is GMPE)
- Stochastic Green's function method, an empirical Green's function method (when the ground motion evaluation method is the fault model)
- Ratio of vertical and horizontal motion response spectra ("V/H spectrum ratio") (for vertical motion)
- Median uncertainty
- Variation and distribution shapes

With regard to the relationship with each seismic source, the MTLAFZ is located near the site, and the sensitivity analysis results revealed its substantial influence. Therefore, a ground motion evaluation method was set up, in which both GMPE and fault models by the characterized seismic source model were used as branches. Moreover, the GMPE and fault model were set as branches for the Gotanda fault, which was a short and isolated active fault distributed near the site. Ground motion evaluations based only on GMPE were used for other seismic sources.

The GMPE supports high reliability within the range of the dataset, whereas the fault model supports high applicability ground motion evaluations near the seismic source, in terms of setting weights. Considering that both methods have numerous application examples in Japan, the weights were determined to be equal and set as 0.5:0.5.

As stated previously, a GMPE that incorporates site corrections for domestic and international GMPEs selected with clear extraction conditions were ultimately considered.

As noted earlier, ground motion evaluations based on the fault model were conducted using the stochastic and empirical Green's function methods after setting the appropriate uncertainty by comparing them with the SCEC BBP models of the United States. However, suitable intraplate crustal earthquakes were not recorded at the Ikata site for elemental earthquakes needed when using the empirical Green's function method; therefore, weights were set as 0.9 and 0.1 for the stochastic and empirical Green's function methods, respectively.

With regard to vertical ground motion evaluation, there were some selected GMPEs that could not directly evaluate vertical motion. Accordingly, settings that considered the V/H spectrum ratio were modeled in horizontal motion. Consequently, the V/H spectrum ratios determined from underground records at KiK-net were considered as branches in addition to those that used the seismic observation records at the Ikata site.

Note that, in the GMC model, branches that express the finite nature of ground motion according to the distribution shape of variations by cutting off the distribution tails were set up.

GMC model logic trees of the MTLAFZ that follow these concepts are shown in Figs. 8–10.

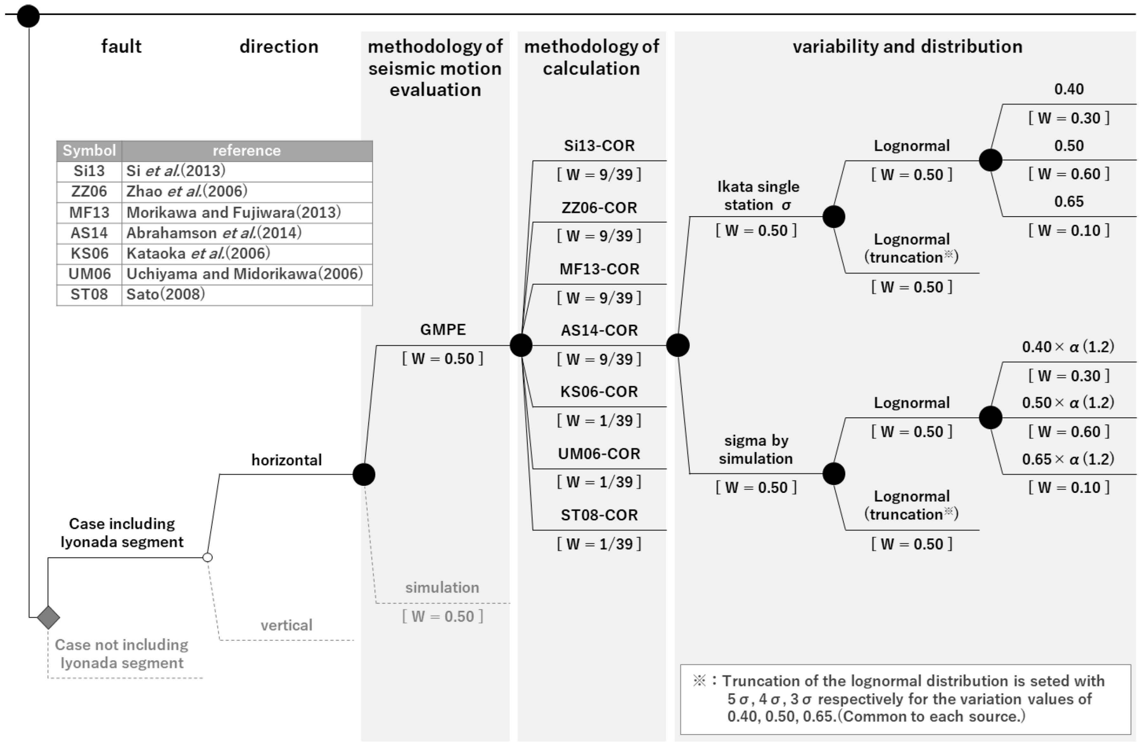

Fig. 8 Example of a logic tree for the GMC model

(MTLAFZ: horizontal motion / GMPE)

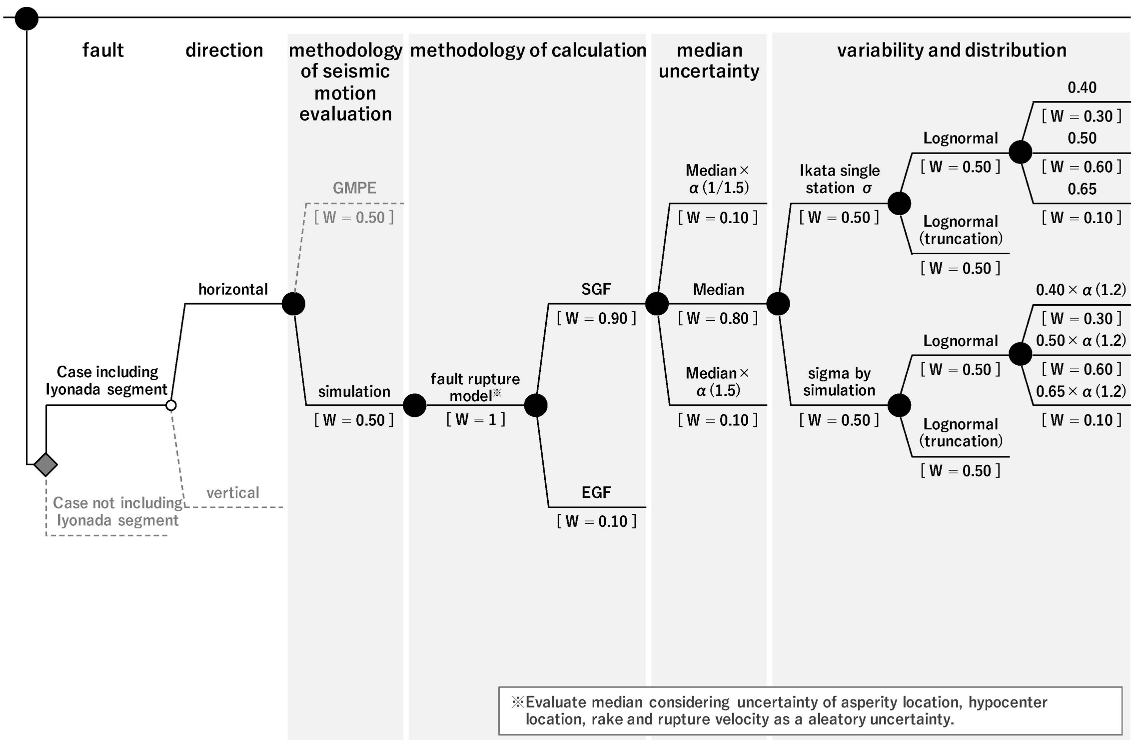

Fig. 9 Example of a logic tree for the GMC model

(MTLAFZ: horizontal motion / fault model)

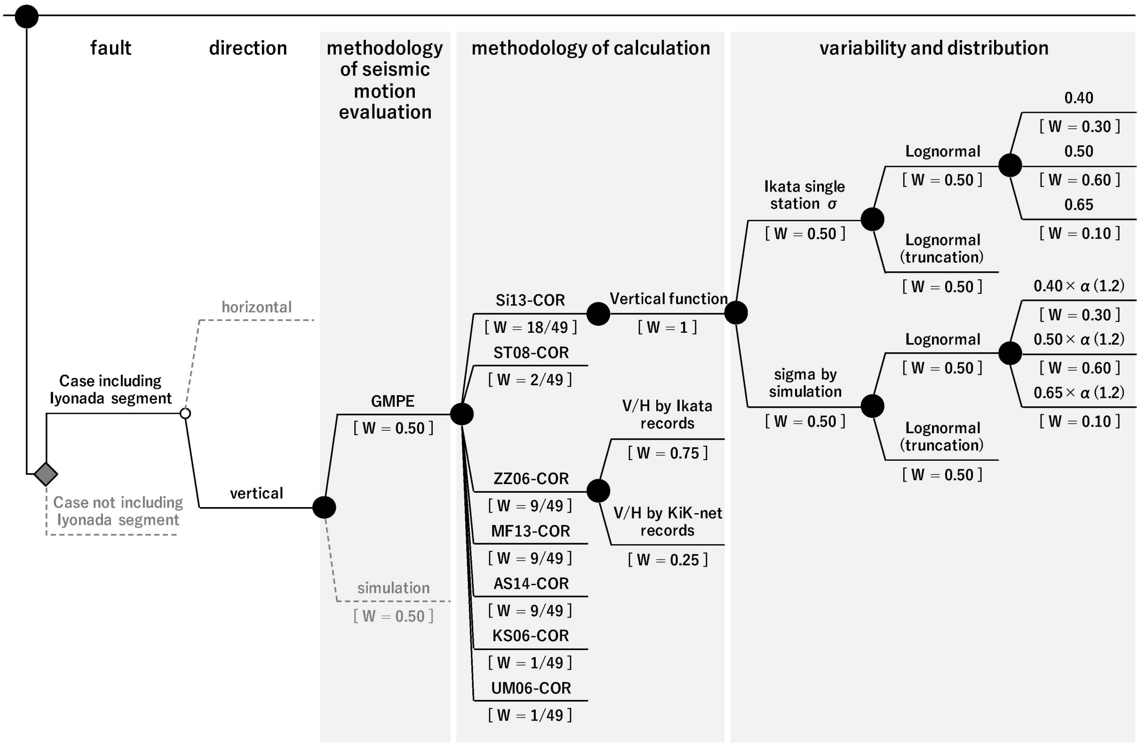

Fig. 10 Example of a logic tree for the GMC model

(MTLAFZ: vertical motion / GMPE)

5. Hazard Analysis Results

This section presents the results of the hazard analysis based on the previously mentioned SSC and GMC models.

As shown in the number of logic tree branches for each seismic source in Table 2, the number of logic tree branches for the MTLAFZ and Nankai Trough Megathrust Earthquake is on the order of 10^5 and 10^3, respectively. Combining these for all seismic sources results in a number of branches on the order of 10^{25} and 10^{26} for the horizontal and vertical motions, respectively, thereby requiring a significant amount of calculation. Therefore, fractile hazard curves between 5% and 95% were first calculated for each seismic source and then combined to calculate the overall hazard curve, which reduced the amount of necessary calculations.

All hazard curves (fractile hazard curves) and uniform hazard spectra at a period of 0.02 s are as shown in Figs. 11 and 12. The mean hazard curve in Fig. 11 is similar to the 84% fractile hazard curve; the overall mean is assumed to be influenced by a branch with an extremely high hazard level in the low-frequency range of less than 10^{-5}. The influence of the MTLAFZ earthquakes is largest in Fig. 12, followed by the influence of the Nankai Trough Megathrust Earthquake. The influence of seismic sources with a relatively large occurrence probability was predominant for blind earthquakes in the Philippine Sea Plate, the Nankai Trough Megathrust Earthquake, and earthquakes smaller than the characteristic scale in areas with low acceleration levels, whereas the influence of blind earthquakes in the landward plate and other active intraplate fault earthquakes were extremely small overall.

It can be seen in the variance contribution plot, which shows the effect of each branch item in the logic tree on the hazard analysis results as a percentage of the overall range of uncertainty, that the calculation method of occurrence probability and GMPE were predominantly influential for the MTLAFZ earthquakes (horizontal motion, GMPE). However, the influence of ground motion scale prediction equations or fault inclination angles, on which expert opinions diverge according to the SSC model, is minimal (Fig. 13). Furthermore, comparisons with GMPE and the fault model indicate that the magnitude relationship between the two varies according to period, but the acceleration level is the same (Fig. 14). Meanwhile, the GMPE influence is largest in the Nankai Trough Megathrust Earthquake (horizontal motion), followed by the source area settings and minimal fault distance calculation method (Fig. 15).

Finally, the uniform hazard spectrum in Fig. 16 shows that the annual exceedance frequency of acceleration on the order of several hundred gal in the Ikata site is 10^{-3}–10^{-4}, while the annual exceedance frequency for major accelerations over 1000 gal is 10^{-5}–10^{-6}.

Table 2　Number of logic tree branches for each seismic source

Earthquake type category	Horizontal	Vertical
MTLAFZ earthquake		
GMPE including Iyo-nada Segment	88,704	152,064
Simulation including Iyo-nada Segment	76,032	114,048
Total	164,736	266,112
Iyo-nada Segment not included	44,352	76,032
Earthquakes smaller than the characteristic scale	84	144
Other active intraplate fault earthquakes		
Other than Gotanda fault	168	288
Gotanda fault GMPE	588	1 008
Gotanda fault simulation	252	504
Total	840	1,512
Blind earthquakes in the landward plate	672	1,152
Blind earthquakes in the Philippine Sea Plate	336	336
Nankai Trough Megathrust Earthquake	1,512	1,512
Total	2.96E+25	7.43E+26

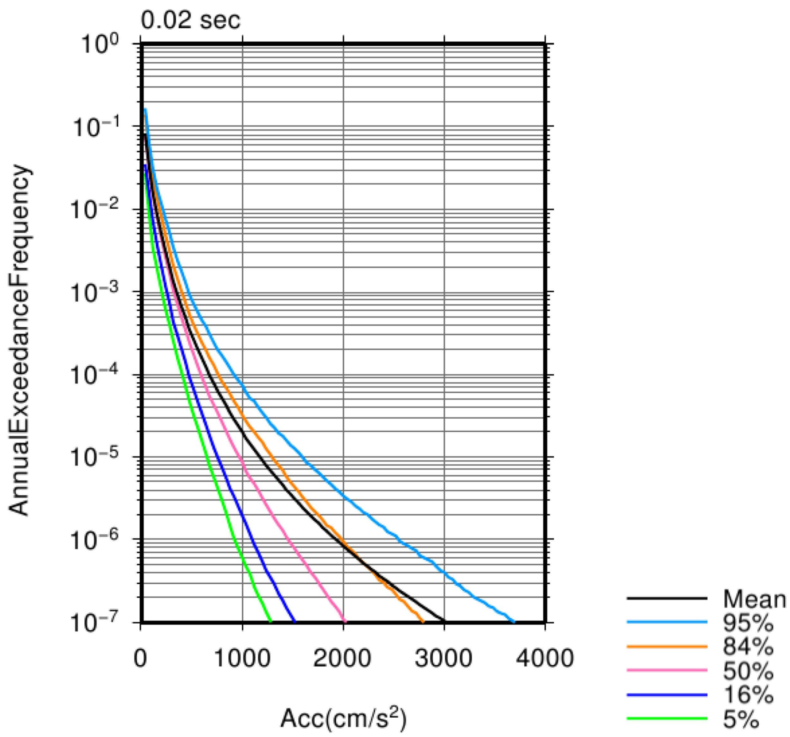

Fig. 11　Final hazard curve distribution showing the mean and percentile hazard curves (horizontal motion / period of 0.02 s)

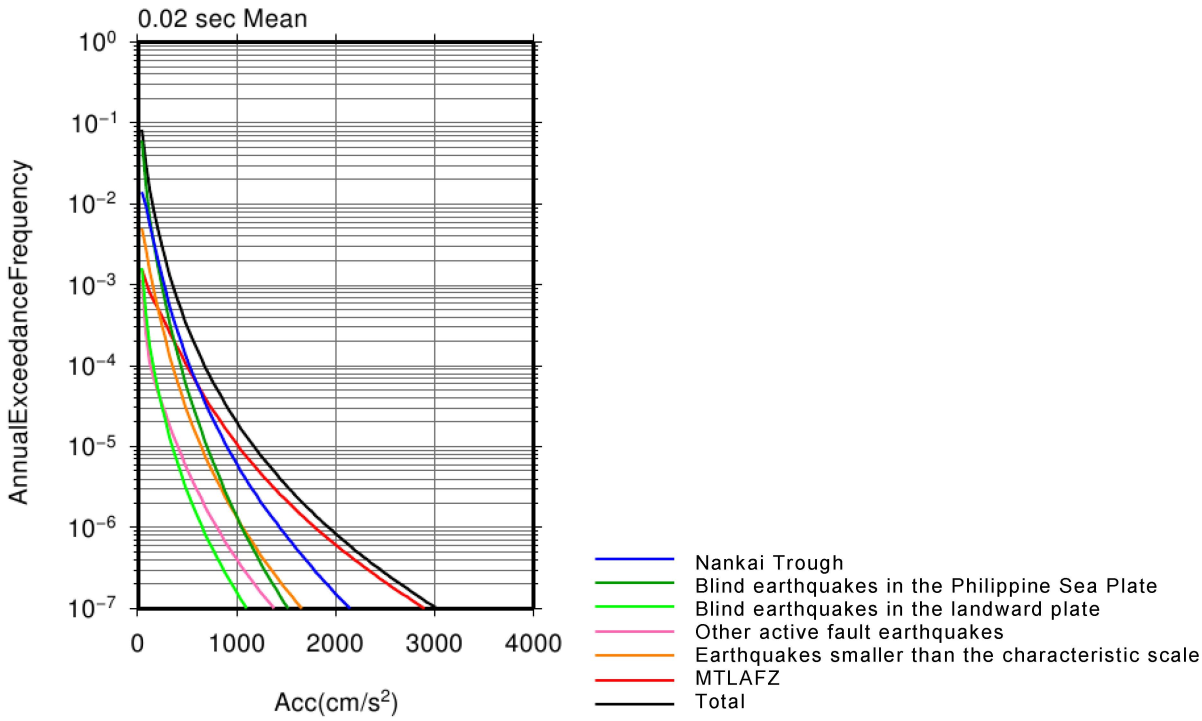

Fig. 12 Hazard curves according to seismic source

(horizontal motion / period of 0.02 s)

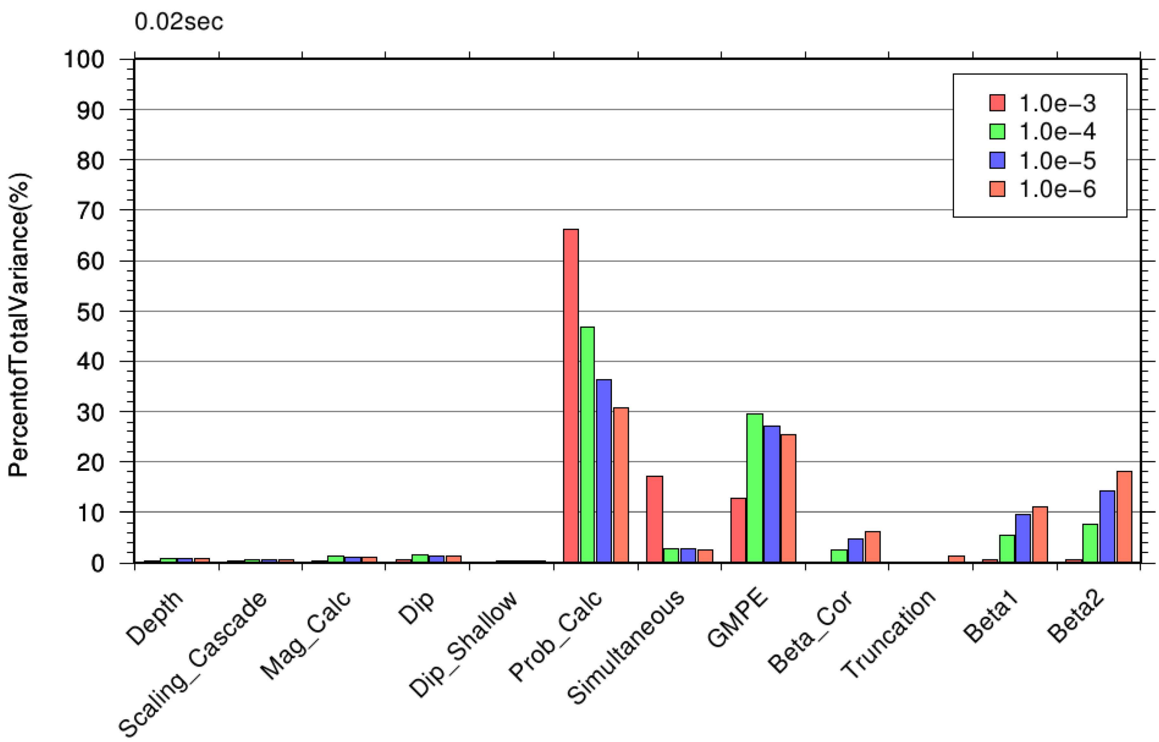

Fig. 13 Variance contribution plot of MTLAFZ earthquakes

(horizontal motion / period of 0.02 s, GMPE)

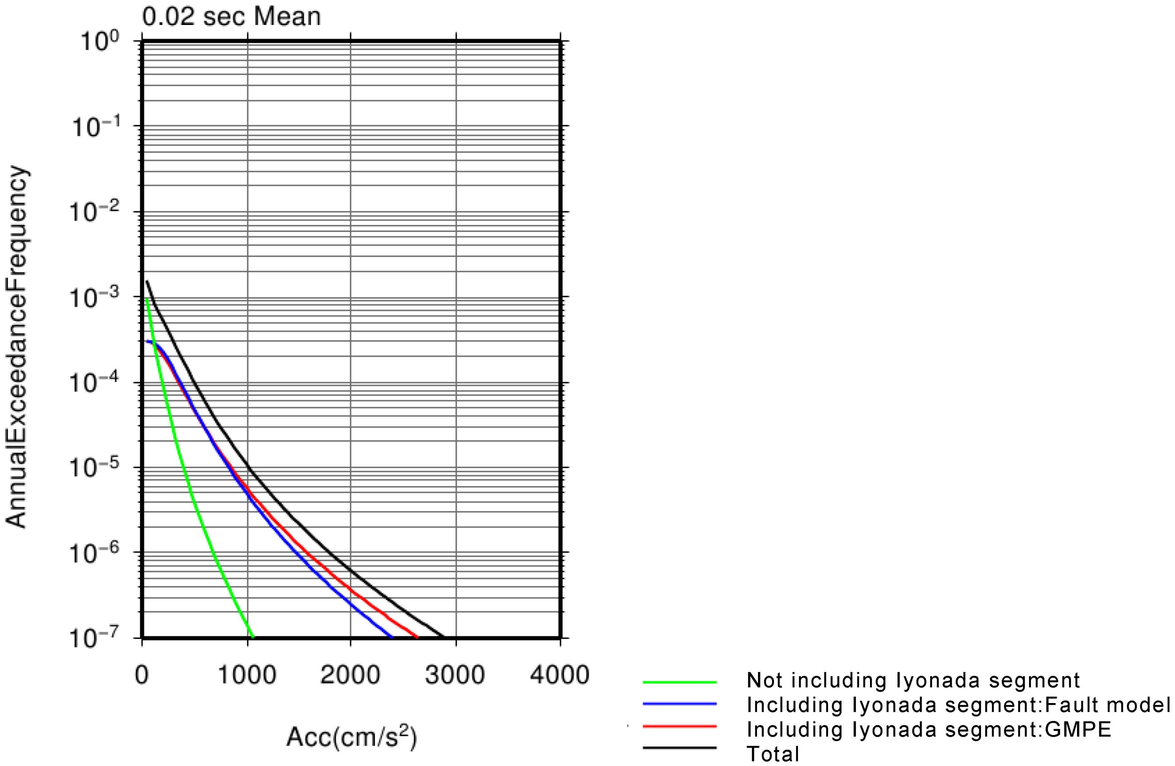

Fig. 14 Comparisons between hazard curves when the Iyo-nada Sea segment in the MTLAFZ earthquake is included or excluded (horizontal motion / period of 0.02 s, average value)

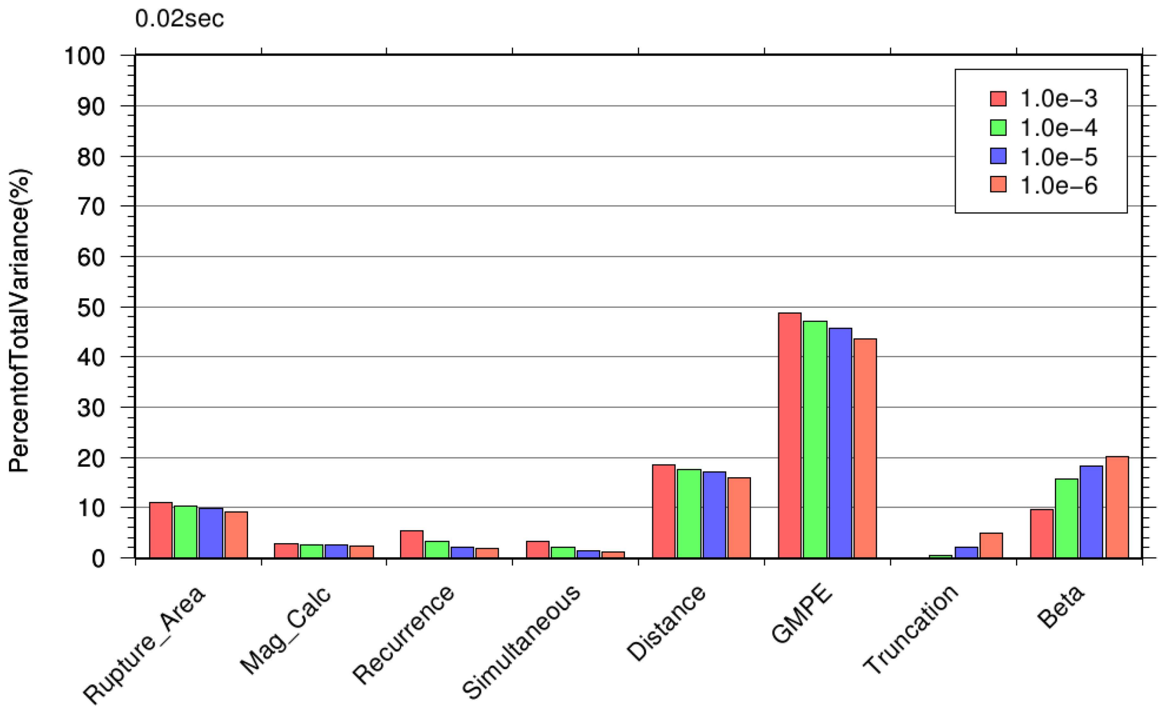

Fig. 15 Variance contribution plot of Nankai Trough Megathrust Earthquake (horizontal motion / period of 0.02 s)

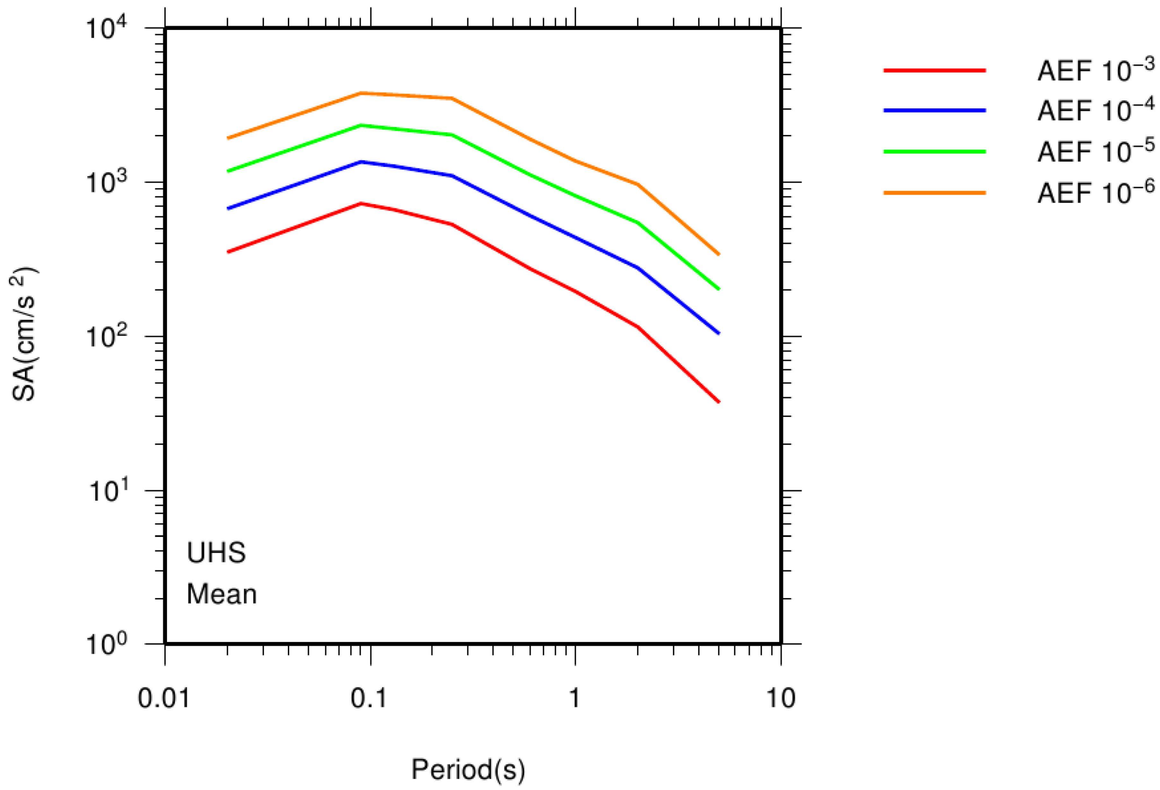

Fig. 16 Uniform hazard spectra for annual frequencies of exceedance of 10^{-3} to 10^{-6} (horizontal motion)

6. Conclusions

This project was aimed at implementing the first SSHAC Level 3 PSHA in Japan. Therefore, all study procedures throughout the project period were performed in accordance with SSHAC Level 3 process and regulatory guidance.

In particular, the project structure, roles and responsibilities of each participant, study items and procedure, PPRP review, and all documented content were implemented according to the SSHAC guidelines.

The seismic tectonics around the Ikata site are characterized by oceanic plates subducting from the south and the central fault of the island arc. This induces megathrust earthquakes occurring at the plate boundary, earthquakes in the oceanic plate, crustal earthquakes due to long strike-slip faults, earthquakes smaller than the characteristic scale occurring at active intraplate crustal faults, earthquakes due to isolated and short active faults, and intraplate earthquakes occurring in areas without any active faults. As a result of constructing a logic tree while achieving the CBR of TDI to comply with SSHAC Level 3 for these various seismic sources, the number of branches reached a value that was unprecedented in Japan. Furthermore, the interlocking evaluation of long faults in the SSC model and the comparative study between the fault model and the SCEC BBP of the U.S. in the GMC model was a pioneering initiative, and these include results that would serve as major references in subsequent projects.

The uniform hazard spectrum revealed that the annual exceedance frequency of acceleration on the order of several hundred gal at the Ikata site was 10^{-3}–10^{-4}, and that of major acceleration over 1000 gal was 10^{-5}–10^{-6}, and

PRA and RIDM can be integrated in the future based on these hazard analysis results. Here, the average hazard curve is similar to the 84% fractile hazard curve, indicating that the branches with an extremely high hazard level in the low-frequency area below 10^{-5} influence the overall average. A major factor for this when considering the perspectives of median value uncertainty is that the ground motion level is clearly significantly evaluated in some GMPEs despite site coefficient corrections as a result of applying multiple GMPEs, including those that are not applicable to hard rocks, such as those at the Ikata site. Considering that the GMPE of next generation attenuation (NGA)-west was studied based on the same ground motion database and that the median value uncertainty was within a narrower range, it is expected that multiple teams will build GMPEs based on the same database in Japan as well as future topics towards further improvements of PSHA.

Accordingly, evaluations of uncertainty, which are essential in evaluating natural external events, were objectively and quantitatively achieved by implementing PSHA at SSHAC Level 3.

The various findings obtained here should be expanded horizontally from seismological perspectives described thoroughly in this report and are important in their applications to future PSHA from the perspective of accurate yet objective evaluations of uncertainty.

＜Acknowledgments＞

The Ikata SSHAC catalog uses the centralized seismic sources of the JMA, and the ground motion database uses the seismic observation records of the National Research Institute for Earth Science and Disaster Resilience (K-NET, KiK-net), JMA, and Port and Airport Research Institute. Altogether, 52 external experts, as REs or PEs, gave valuable lectures and discussions at Workshops #1 and #2, and the lecture materials were incorporated into a database for model construction. Shunichi Nomura gave a lecture at Workshop #2 as a PE, after which the variation of activity intervals in the MTLAFZ were calculated, and these results were adopted in the SSC model. The five PPRP members, including the chairman Kojiro Irikura, Atsumasa Okada, Tadashi Annaka, Ken Ugata, and Martin McCann, provided comments necessary for ensuring that the entire project followed the SSHAC Level 3 requirements as well as a polite yet appropriate review of the final report manuscript.

George Apostolakis and Kevin Coppersmith, who participated as advisers with experience in SSHAC, provided valuable advice on both procedure and technology throughout the entire project.

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