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DEVELOPMENT OF MODEL OF SEISMIC SOURCE CHARACTERISTICS AT THE IKATA SITE BASED ON GUIDELINES FOR SSHAC LEVEL 3

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ABSTRACT: The 2011 off the Pacific coast of Tohoku Earthquake and the 2016 Kumamoto Earthquake have increased the interest in the seismic hazard assessment. As new knowledge has been revealed with every new major earthquake, it is important to consider the range of the uncertainty of the parameters which are needed to the assessment and to understand the impact of each earthquake by probabilistic seismic hazard analysis, in advance. The Ikata SSHAC project is the first attempt in Japan to apply SSHAC Level 3 to the probabilistic seismic hazard analysis. In this paper, we report on the results of the modeling of various seismic sources, which include the Median Tectonic Line fault zone which is a long active fault and trench earthquakes occurring in the Nankai Trough. In addition, we discuss the effectiveness of guidelines for SSHAC Level 3, the range of the uncertainty and on the impact on the seismic hazard, because the gained knowledge and know-how of the scope would be useful for subsequent studies.

Keywords: *Probabilistic seismic hazard analysis, SSHAC level 3, Median tectonic line*

active fault zone, Nankai trough, Seismic source characterization

1. INTRODUCTION

Japan is an earthquake-prone country and the M9 2011-off-the-Pacific-coast-of-Tohoku Earthquake was the largest earthquake ever recorded in Japan. In the wake of the earthquake and the subsequent accident at Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station, there has been much more interest in seismic hazard assessments for nuclear power plants and other critical facilities. Assessments of natural phenomena inherently involve a variety of uncertainties; with respect to earthquakes, it is important to study the factors and ranges of uncertainties of the parameters required to evaluate and forecast future events, and then to assess their impacts in advance through probabilistic seismic hazard analysis (PSHA).

The uncertainties considered in PSHA can be broadly classified into two types: "aleatory variability" caused by the randomness of natural phenomena and "epistemic uncertainty" caused by inadequate understanding due to lack of data and experience. The former is modeled using probability distributions whereas the latter is modeled using logic trees. To set branches and weights in a logic tree, a quantitative assessment is performed based on the aggregated opinions of experts[1), 2)]. If there are insufficient reliable data on parameters, we have to rely on the comprehensive judgment of experts based on their experience, although concrete examples of such cases are still scarce. For example, in the case of developing seismic source characterization models that take the linkage of long active faults into account, it has been pointed out that, compared to the long history of analyzing logic trees in the United States, in Japan there is a need to accumulate more knowledge and experience in the appropriate selection of experts and how to conduct expert discussions[3)].

In the United States, two major research institutes independently carried out probabilistic seismic hazard analyses in the 1980s, which led to the problem of very large discrepancies between the mean values in their results. The U.S. Nuclear Regulatory Commission, U.S. Department of Energy, and the Electric Power Research Institute established the Senior Seismic Hazard Analysis Committee (SSHAC) to study the cause and conduct an investigation, which revealed that the cause of the discrepancy was not in the technical aspect but in the procedures used by experts to consider uncertainties[4)]. Based on this experience, guidelines were established in 1997 to provide procedures for conducting studies that take transparency into account and clearly define the roles and responsibilities of the people involved in the studies[5)]. The guidelines defined four levels according to the importance and degree of uncertainties of the facility in question. Level 3 has been applied mainly to studies of nuclear installations in the United States and other countries. With more cases applying SSHAC Level 3 and the development of further guidelines to address careful deliberations and objectivity of the discussions, the guidelines published in 2012 and revised in 2018[6), 7)] have now become the standard. Kameda[8)] referred to these guidelines as the SSHAC Level 3 Guidelines, which we adopted in this paper. The most important concept in these guidelines to evaluate uncertainty is developing models based on the "center, body, and range of technically defensible interpretations" (CBR of TDI). Note that in this paper, the "center" in the SSHAC Guidelines refers to the "central point/value" of expert opinions and does not correspond to the statistical term "median." The SSHAC Level 3 Guidelines provide detailed study procedures, including formal procedural descriptions, to eliminate bias as much as possible, and may therefore be considered as presenting a rational study procedure for creating models based on CBR of TDI. In other words, it must be fully understood that the essence of the SSHAC Level 3 Guidelines is not achieved by following the "formal study procedures," but in how well the models based on CBR of TDI are developed.

The Ikata SSHAC Project was conducted by the Shikoku Electric Power Company and the Nuclear Risk Research Center of the Central Research Institute of Electric Power Industry to perform the first PSHA using SSHAC Level 3 in Japan, with the aim of further improving the safety of the Ikata Nuclear Power Plant located in northwestern Shikoku[9)]. Enhancing the "accountability," "quality," and "transparency" of risk assessments based on PSHA is essential for electric power companies involved in the operation of nuclear power plants, in order to promote calm and rational discussions on the future of nuclear power in Japan[8]. To perform the PSHA for the Ikata site, a team of experts to evaluate seismic source characterization (SSC) (called the SSC Team) and another team of experts to evaluate ground motion characterization (GMC) (called the GMC Team) were established, and technical studies were carried out from spring 2016 to fall 2020 with the Project Technical Integrator overseeing the overall direction of discussions for both teams. Various seismic sources, including long active intraplate faults and megathrust earthquakes, and the ground motions they cause were modeled based on CBR of TDI; the entire process and basis were published as the Ikata SSHAC Project Final Report[10] on the Shikoku Electric Power Company's website in accordance with the SSHAC Level 3 Guidelines. Of the results of the Ikata SSHAC Project conducted by the two teams given above, this paper focuses on the SSC models and discusses the effectiveness of the SSHAC Level 3 Guidelines as well as the range of uncertainty and impact on seismic hazard of each evaluation parameter, with the belief that the knowledge and know-how gained from the project are bound to benefit future studies. For the GMC models used in the Ikata SSHAC Project, see the paper produced by the GMC team, Fujiwara et al.[11]

2. SEISMOTECTONICS AROUND THE IKATA SITE

The Ikata site is located near the base of Sadamisaki Peninsula on the north side in the northwestern part of Shikoku, and sits on top of the continental Eurasian Plate (Amur Plate) with the oceanic Philippine Sea Plate subducting in the northwest direction from the Nankai Trough in the south (Fig. 1(a)). Observations of seismicity around the Ikata site show greater seismicity with increasing focal depth in the northwest direction corresponding to the subduction of the Philippine Sea Plate, while shallow intraplate crustal earthquake activity is very low (Fig. 2(a)). Destructive earthquakes in the past include interplate earthquakes that recur along the Nankai Trough at 100- to 150-year intervals such as the 1946 Nankai Earthquake (M_J 8.0), oceanic intraplate earthquakes that strike at slightly deep areas from the western part of the Seto Inland Sea to near the Bungo Channel such as the 2001 Geiyo Earthquake (M_J 6.7), as well as intraplate crustal earthquakes that originate from active faults such as the 1596 Keicho-

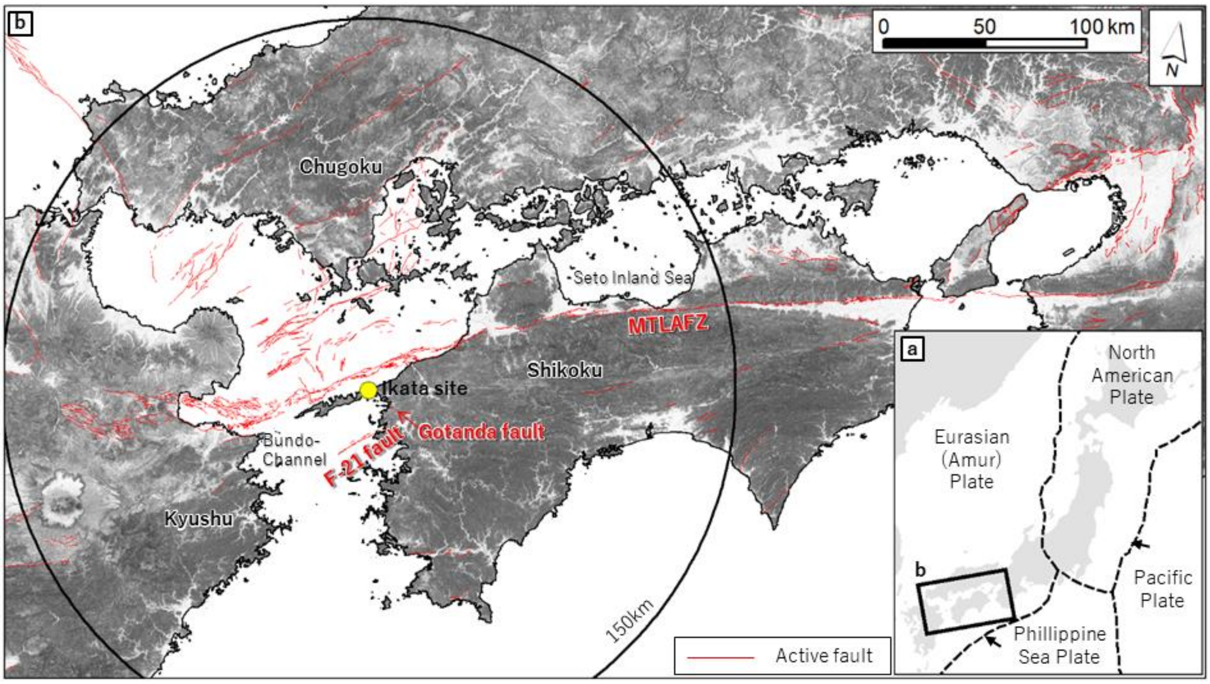
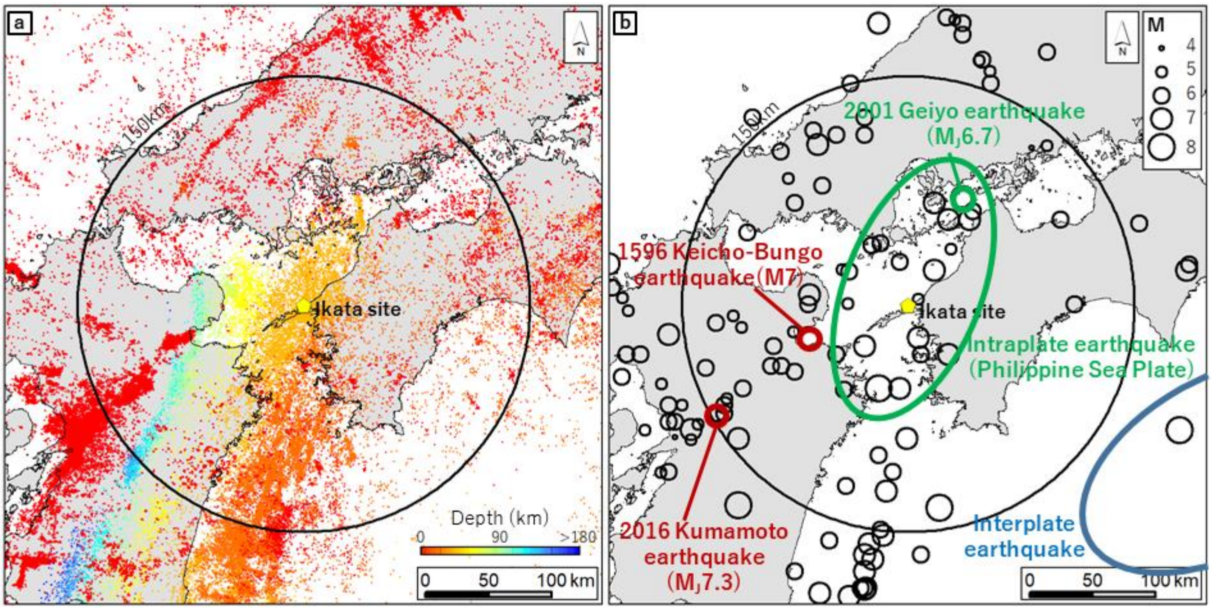


Fig. 1 Active fault distribution and tectonics. Active fault distribution is based on the compilation of maps in the Ikata SSHAC Project Final Report[10].



(a) Hypocenters map (b) Distribution of major destructive earthquakes

Fig. 2 Seismicity around the Ikata site. The seismic source distribution shown in (a) is based on the JMA unified earthquake catalog for earthquakes over M1 from October 1997 to May 2016. The locations of epicenters of destructive earthquakes shown in (b) is based on the Ikata SSHAC Project Final Report[10].

Bungo Earthquake (M 7) and the 2016 Kumamoto Earthquake (M_J 7.3) (Fig. 2(b)).

The Median Tectonic Line (MTL) runs close to the Ikata site and divides the geological structure of southwestern Japan into inner and outer zones. The part of the MTL from western Kii Peninsula to Shikoku consists mainly of right-lateral strike-slip active faults striking east-northeast to west-southwest (Fig. 1(b)); this part of the MTL is considered to be the central fault of the island arc caused by oblique subduction of the Philippine Sea Plate[12]. This active fault is one of the longest in Japan and is called the Median Tectonic Line active fault zone (MTLAFZ). The Ikata site is located in the transition zone of the fault zone between eastern Shikoku, which has mainly strike-slip components and includes reverse fault components, and Kyushu, which has strike-slip components with normal fault components. The transition zone is under a crustal stress field with east-west compression[13]. MTLAFZ passing north offshore of the Ikata site is a dextral strike-slip fault with a small normal fault component, and is the closest active intraplate fault to the site. Furthermore, aside from the MTLAFZ, the Gotanda, F-21, and other strike-slip active faults running east-northeast to west-southwest are distributed around the Ikata site (Fig. 1(b)).

The Ikata site is located near the northern limit of the focal region of very large interplate earthquakes (ranging about M 8 to M 9) that recur in the Nankai Trough. Additionally, interplate earthquakes (about M 8 or less) and oceanic intraplate earthquakes (about M 7 or less) occur at slightly deep areas near the Ikata site as earthquakes connected to the subduction of the Philippine Sea Plate. Furthermore, for intraplate crustal earthquakes, aside from earthquakes occurring in active intraplate faults such as the MTLAFZ, relatively large earthquakes may occur in areas where active faults have not yet been identified.

Thus, the seismotectonics around the Ikata site are complex. Accordingly, six types of earthquakes were used to conduct the evaluation: (1) MTLAFZ earthquakes, (2) other active intraplate fault earthquakes, (3) the Nankai Trough Megathrust Earthquakes, (4) blind earthquakes in landward plates, (5) blind earthquakes in the Philippine Sea Plate, and (6) earthquakes smaller than the characteristic magnitude of active intraplate faults. For earthquakes smaller than the characteristic magnitude, based on the lessons learned from the 2016 Kumamoto Earthquake foreshock (M_J 6.5 earthquake that struck on April 14, 2016) with a seismic intensity of 7 on the Japanese magnitude , in order to eliminate any "gaps" in the seismic hazard evaluation, we revised the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion (HERP)[14)] definition "earthquakes whose activities are difficult to trace from surface evidence." Our new definition adds earthquakes that are magnitudes smaller than the characteristic magnitude to the original definition of earthquake activity that does not leave traces on the surface.

3. PROCEDURE AND SIGNIFICANCE OF THE SSHAC LEVEL 3 GUIDELINES

The Ikata SSHAC Project is the first implementation of PSHA using SSHAC Level 3 in Japan. The project started with receiving training on the history of SSHAC studies in the United States and the significance, purpose, contents, and procedures of the SSHAC Level 3 Guidelines from overseas advisors with extensive experience in SSHAC projects. We carried out sequential interviews with overseas advisors from the beginning until the end of the project with regard to the process of implementing the SSHAC Level 3 Guidelines. With the aim of developing a model that appropriately reflects seismic characteristics in Japan and based on the premise that all requirements given in the SSHAC Level 3 Guidelines are satisfied, as well as taking into account the differences in industrial structure and culture between Japan and the United States, we looked for ways to proceed with the discussions that align with the actual circumstances in Japan. At the beginning, we were unfamiliar with the process of the SSHAC Level 3 Guidelines; as mentioned in the previous section, there were a variety of seismic sources around the Ikata site combined with a wide range of parameters to evaluate for each source, which made it difficult to conduct effective discussions within the SSC Team. In addition, the SSHAC Level 3 Guidelines stipulate that in principle all members of the team participate in face-to-face discussions. With the difficulties in coordinating the schedules of the SSC Team, which was mainly composed of participants from universities and research institutes, we had to maximize the productivity of the discussions. Therefore, we decided to conduct the expert discussions by first broadly dividing the six types of earthquakes for evaluation into three parameters: (a) location and geometry, (b) magnitude, and (c) probability of occurrence, and placing them in a matrix format for clarity (Table 1). This approach was well received by the overseas advisors.

The process of the SSHAC Level 3 Guidelines calls for identifying the evaluation parameters that have a large impact on earthquake hazard, called "Hazard Significant Issues (HSI)", at the early stage of the project in order to conduct particularly extensive database collection. For the Ikata SSHAC Project, based on the analysis results of PSHA of the Ikata site conducted in the past, we selected all the parameters—(a) location and geometry, (b) magnitude, and (c) probability of occurrence—as HSIs for (1) MTLAFZ earthquakes close to the Ikata site; for all other earthquake types besides (2) other active intraplate fault earthquakes, we selected (b) magnitude and (c) probability of occurrence as HSIs (Table 1). After exhaustively collecting HSIs and their relevant data, a total of 34 outside experts gave briefings at open workshops on particularly important data, including those that were jointly discussed with the GMC Team (Table 2), providing deeper understanding for the SSC Team. Prior to the discussions, we analyzed the relationships between the content of the briefings requested from outside experts and the factors that cause uncertainty to identify the points at issue in advance. At this time, in accordance with the SSHAC Level 3 Guidelines, we did not engage in any discussion concerning model development to avoid bringing bias into the investigation of the model in the first half of the study. The purpose of the discussions was limited to impartially reviewing the contents of the data that will form the basis of model development, such as offshore acoustic exploration records presented by outside experts. Through such discussions, a general consensus was reached on the uncertainties inherent in the data that will form the basis of the SSC model construction to an extent that is not affected by the differences in expertise of the SSC Team members. Not going into discussions of models at the data review stage is an example of a specific review procedure in the SSHAC Level 3 Guidelines to avoid bias and capture the CBR of TDI. Some of the outside experts included people involved in the Ikata SSHAC Project, and we noted that it was necessary to clearly distinguish their dual positions and act according to their position at that point in time. This is also an important guideline stipulated in the SSHAC Level 3

Table 1 Main SSC model parameters and hazard significant issues for each earthquake type

Main seismic source characterization parameters	(a) Location and Geometry	(b) Magnitude	(c) Probability of Occurrence
(1) MTLAFZ earthquakes	Location, Segmentation, Fault plane top and bottom (Fault rupture area and Source fault), Dip angle	Magnitude evaluation methodology of linked earthquakes, Magnitude prediction equations based on fault length or fault area, Dip angle	Methodology for evaluating mean recurrence interval, Slip rate, Displacement per event, Time-dependent or Time-independent occurrence models, Elapsed time since the latest faulting event, Aperiodicity parameter, Methodology for evaluating seismic linkage
(2) Other active intraplate fault earthquakes	Location (Target active fault, Existence or non-existence), Fault plane top and bottom (Fault rupture area and Source fault), Dip angle	Magnitude prediction equations based on fault area, Setting magnitude, Dip angle	Methodology for evaluating mean recurrence interval, Slip rate, Displacement per event, Time-dependent or Time-independent occurrence models, Elapsed time since the latest faulting event, Aperiodicity parameter
(3) Nankai Trough Megathrust Earthquakes	Assumed focal regions, Fault plane top and bottom	Magnitude prediction equations	Mean recurrence interval, Elapsed time since the latest faulting event, Aperiodicity parameter, Time-dependent or Time-independent occurrence model, Methodology for evaluating seismic linkage
(4) Blind earthquakes in landward plates	Regional division setting, Depths of the seismogenic layer top and bottom, Layout of seismic sources	Maximum magnitude	Earthquake catalog, G-R law setting, Time-independent occurrence model
(5) Blind earthquakes in the Philippine Sea Plate	Regional division setting, Plate geometry, Ratio of interplate to intraplate earthquake, Layout of seismic sources	Maximum magnitude of intraplate and interplate earthquakes	Earthquake catalog, G-R law setting, Time-independent occurrence model
(6) Earthquakes smaller than the characteristic magnitude	Layout of seismic sources	Maximum magnitude	Frequency of occurrence, Time-independent occurrence model

HSI

Guidelines to prevent project participants from engaging in deeper discussions that lead to their own theories being adopted. The members comprising the SSC Team were required to have sufficient expert knowledge and the ability to discuss from a wide range of perspectives. They were also required to be impartial evaluators who could construct models based on the CBR of TDI without being bound by their own theories and ideas. We therefore made sure that all of the SSC Team members possessed these qualities and included experts with thorough knowledge of the MTLAFZ, which was thought to have the greatest impact on the Ikata site.

We started working on model development after completing two open workshops with invited outside experts. First, for each earthquake type from (1) through (6) given above, we comprehensively listed the possible branch parameters from the data collected for each of the following: (a) location and geometry, (b) magnitude, and (c) probability of occurrence, and discussed the setting of branch parameters for logic trees. Next, each member first expressed their own opinions on the weights to be given to each branch parameter and their proposed distribution, after which the SSC Team thoroughly discussed the appropriate weights from the standpoint of the CBR of TDI until a consensus was reached. We then presented the models constructed at this stage to overseas advisors for consultation and made the necessary modifications. After this process, we created preliminary models and checked the results of the hazard analysis and sensitivity analysis based on these models at the third open workshop. Here, the SSC Team presented the validity of their developed models, which then underwent a review by five experts comprising the Participatory Peer Review Panel (PPRP). The PPRP was established to rigorously verify whether the process and technical content of the series of studies conducted by the team adhered to the SSHAC Level 3 Guidelines. By checking the analysis results and receiving appropriate feedback from the PPRP at the open workshop, we were able to shed light on the areas that needed modification in the preliminary models. The final models were developed with the necessary revisions after further discussion within the SSC team. We presented the final models to the PPRP at a meeting called the PPRP Briefing, made revisions in light of the feedback from the briefing, and finalized the models. The process of the SSHAC Level 3 Guidelines was carried out using impartial expert judgment to evaluate uncertainties that were difficult to address statistically or mechanically, such as weight setting. The SSC Team carried out exhaustive discussions based on a huge volume of documents until reaching a consensus, so that differences in weight coming from a single significant digit were significant to the process and results of the SSHAC Level 3 Guidelines. Thus, the SSC models of the Ikata SSHAC project were completed through careful deliberations in accordance with the procedures of the SSHAC Level 3 Guidelines, with the SSC Team taking responsibility for the technical study and its overall results.

The steps given above have led to stable logic trees that provide results that are "descriptive," and with "quality" and "transparency." As the first project in Japan to faithfully implement the procedures of the SSHAC Level 3 Guidelines, the Ikata SSHAC Project was a voluntary effort by a power plant operator that carried great significance in its attempt to refine scientific and technical evaluation methodologies for seismic hazard assessment by systematically analyzing the causes of uncertainty at a level beyond the current state of Japanese regulations.[8)]

Table 2 Topics of presentations by outside experts

WS	Content	Presenter		WS	Content	Presenter	
1	Seismic activity around the site and the Shikoku area	Shiomi Katsuhiko (NIED)	RE	1	Relationship between appearance ratio of surface fault and magnitude at diffuse seismicity	Dan Kazuo (ORI)	RE
1	The GPS data in Shikoku and its surrounding area	Noda Akemi (KKE)	RE	1	"Earthquakes that do not show signs on the surface" and "Earthquake that does not show a direct relation with an active fault" by HERP	Oshima Mitsutaka (Shimuzu Co.)	RE
1	Construction of deep seismometers and thickness of the seismogenic layer around the site	Nishizaka Naoki (SEPCO)	RE	1	Distribution and characteristics of appeared surface fault by the 2014 Northern Nagano (Kamishiro fault) earthquake	Matta Nobuhisa (Okayama Univ.)	RE
1	Evaluation of subsurface structure by seismic ground motion records of Ikata NPP(Analysis of each arrival direction of seismic wave)	Ogawa Hiroshi (SEPCO)	RE	2	Crustal Stress Fields and active fault activity in South-western Japan	Miyakawa Ayumu (AIST)	PE
1	Deep seismic ground motion records of Ikata NPP and Q-value	Sato Hiroaki (CRIEPI)	RE	2	GNSS data and shear zone in South-western Japan	Nishimura Takuya (Kyoto Univ.)	PE
1	Topographic and geological characteristics and the distribution of active faults around the site	Onishi Kozo (SEPCO)	RE	2	Substantiality of an earthquake and a tsunami of M9 class in Nankai trough	Fujiwara Osamu (AIST)	PE
1	Geological Map of Japan 1:200,000. Matsuyama (2nd ed.) (Geology and distribution of active faults)	Miyashita Yukari (AIST)	RE	2	The tsunami sediment survey in the Amida-ike in West end of the Sadamisaki Peninsula	Yanagida Makoto (Hanshin Con.)	RE
1	Acoustic survey in the Iyo-nada area and the distribution of active faults	Takahashi Kyohei (SOGO)	RE	2	Earthquake long-term forecast on active faults by Bayesian prediction	Nomura Shunichi (Tokyo Tech.)	PE
1	Deep subsurface structure in the Iyo-nada area	Nishizaka Naoki (SEPCO)	RE	2	Slip rate of the MTL by GPS data	Aoki Yosuke (Univ. of Tokyo)	PE
1	Seismic attributes analysis and CRS stacked method in the Iyo-nada area	Tsuji Takeshi (Kyushu Univ.)	RE	2	Displacement and Slip rate of the MTL by Tectonic geomorphology	Goto Hideaki (Hiroshima Univ.)	PE
1	Paleoseismological data and slip amount of the MTL fault zone	Ikeda Michiharu (SRI)	RE	2	Historical documents of the Keicho-Bungo and Keicho-Iyo Earthquake	Hirai Yoshito (HTHM and HBHM)	PE
1	Offshore boring and Acoustic survey in the area of Iyo-nada to Saganoseki	Nanayama Futoshi (AIST)	RE	2	Location of the MTL in the Iyo-nada Sea and Beppu bay area	Hayasaka Yasutaka (Hiroshima Univ.)	PE
1	Examples of segmentations of the MTL fault zone	Ikeda Michiharu (SRI)	RE	2	Magnitude-Frequency Statistics & Seismic Hazard	Mark W. Stirling (Univ. of Otago)	PE
1	Earthquake in/on the Philippine Sea Plate (Evaluation by HERP)	Oshima Mitsutaka (Shimuzu Co.)	RE	2	Data of acoustic surveys in the Iyo-nada sea area around the MTL	Takahashi Kyohei (SOGO)	RE
1	Reevaluation of magnitudes of damaging earthquakes in/on the Philippine Sea Plate	Kanda Katsuhisa (KRCI)	RE	2	Earthquake magunitude estimated from active faults	Takemura Masayuki (Nagoya Univ.)	PE
1	Seismogenic environments of intraslab earthquakes in the Philippine Sea Plate Around the Ikata NPP	Ogawa Hiroshi (SEPCO)	RE	2	Dynamic rupture simulations of strike-slip fault on dip angle	Takahama Tsutomu (KKE)	PE
1	Case of the zoning of seismotectonic provinces and an earthquake that does not show a direct relation with an active fault	Aoyagi Yasuhira (CRIEPI)	RE	2	Model tests of strike slip on dip angle fault	Ueta Keiichi (CRIEPI)	PE

*At Workshop 1 (WS1), discussions were carried out with resource experts (REs) explaining data that may be used for evaluation. At Workshop 2 (WS2), in addition to REs, discussions were carried out with proponent experts (PEs) explaining particular models or methodologies that may be used for evaluation.

4. SSC MODEL DEVELOPMENT BASED ON SSHAC LEVEL 3 GUIDELINES

Of the six types of earthquakes expected around the Ikata site, MTLAFZ earthquakes, other active intraplate fault earthquakes, and the Nankai Trough Megathrust Earthquakes are earthquakes with set specific seismic source fault planes. After specifying the location and geometry of seismic sources, we constructed the logic tree to set the magnitude and probability of occurrence of the earthquakes (Fig. 3a). On the other hand, the remaining types of earthquakes: blind earthquakes in landward plates, blind earthquakes in the Philippine Sea Plate, and earthquakes smaller than the characteristic magnitude of active intraplate faults are earthquakes with no set individual seismic source fault planes. After evaluating the locations where seismic sources may be distributed and the maximum magnitudes of earthquakes that may occur at these locations, we constructed the logic tree for earthquake groups that increase in frequency with smaller magnitudes according to the Gutenberg–Richter law (G–R law) (Fig. 3b). Since the framework of the constructed SSC models greatly differ depending on whether specific seismic sources were set or not, the components of each are broadly classified and described below. For details on logic trees and the basis for setting the SSC models, see the Ikata SSHAC Project Final Report[10].

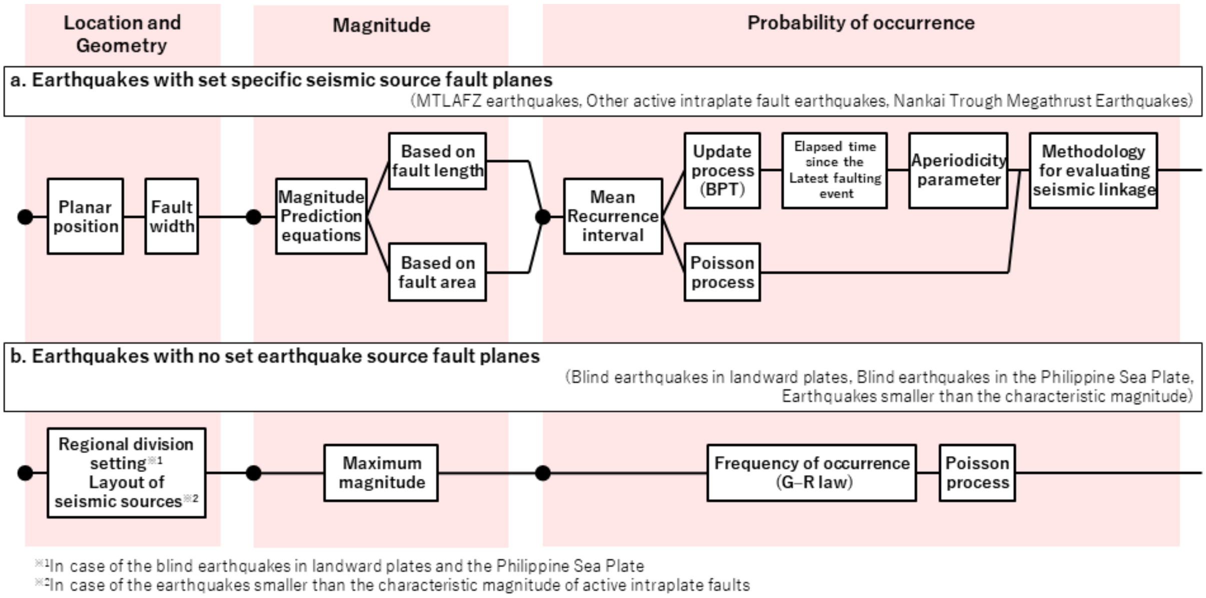


Fig. 3 Overview of the SSC model (logic tree)

4.1 SSC models of earthquakes with set specific seismic source fault planes

4.1.1 SSC models of earthquakes on the MTLAFZ

(1) Modeling the location and geometry

The evaluation parameters for location and geometry of earthquakes with set specific seismic source fault planes, which includes MTLAFZ earthquakes, are planar position and fault width (Fig. 3a). For MTLAFZ earthquakes, this also includes segmentation, depths of the fault plane top and bottom (fault rupture area and source fault), and fault dip angle. Since the fault dip angle is also closely related to magnitude, in model development we classified it as a parameter related to the magnitude evaluation of earthquakes. Planar position refers to the surface distribution of active faults, which are slightly different in large-scale maps depending on the reference document used, although they are all generally the same from the perspective of seismic ground motion evaluation. In light of this, we adopted the most accurate active fault distribution (Fig. 1), which was compiled and created by the SSC Team based on the latest edition of the Active Fault Map in Urban Area published by the Geospatial Information Authority of Japan for the land area and the active fault distribution by Nanayama et al.[15] for the surrounding waters of the Iyo-nada Sea. At the Iyo-nada Sea offshore of the Ikata site, since the principal faulting on the MTLAFZ cuts the sediment layer reaching the seabed at a high angle (nearly vertical) approximately 8 km offshore, the source fault was also set to run across approximately 8 km offshore (Fig. 4). The active fault groups south of this principal faulting (5–8 km offshore of the Ikata site) was judged to be distributed faulting that occurred as a result of the activity of the principal fault. For segmentation, we adopted the divisions set in accordance with the concept of earthquake, geometric, and behavioral segments[16] based on the active fault distribution (Fig. 4 and Table 3). The segmentation was generally consistent with previous approaches (Nanayama et al.[15], HERP[17), 18)], and Yoshioka et al.[19]). Differences in detail was considered to be largely due to the resolution of the active fault distribution used as the basis for segmentation and their interpretation. In segmenting the MTLAFZ, we used our newly compiled and created active fault distribution, the most accurate to date, and took note of the presence of step faults that are over several kilometers in width and sedimentary basins that reach the top of the seismogenic layer. We were thus able to judge that there was no significant epistemic uncertainty. Consequently, we divided the MTLAFZ into eight segments, including the 54 km long Iyo-nada Segment closest to the Ikata site. Since the MTLAFZ is an active fault that reaches the surface, we only used a depth of 0 km (ground surface) for the top of the fault rupture area for calculating magnitude and initially set the depth of the top of the source fault that produces short-period strong ground motions to 2 km and 3 km branches. After confirming that the impact on seismic hazard is small, we used only the 2 km branch corresponding to the depth of the meeting point of the Sambagawa metamorphic rocks and the Ryoke granite. We assumed that the depths of the fault rupture area bottom and source fault bottom were the same and set branches for 15 km and 18 km. At the northwestern part of Shikoku where the Ikata site is located, the seismic source distribution is shallower than that in the central eastern part of Shikoku; various types of data on the bottom of the seismogenic layer, such as seismicity and crustal heat flow, comprehensively support the 15 km depth, whereas the MTLAFZ as a whole, including the central eastern part of Shikoku, supports the 18 km depth. In light of this, we attached greater importance to including the entire region and judged that the center of the body of opinions for the bottom of the seismogenic layer of the entire MTLAFZ is 18 km. Therefore, we set the weights of 18 km and 15 km to 0.7:0.3.

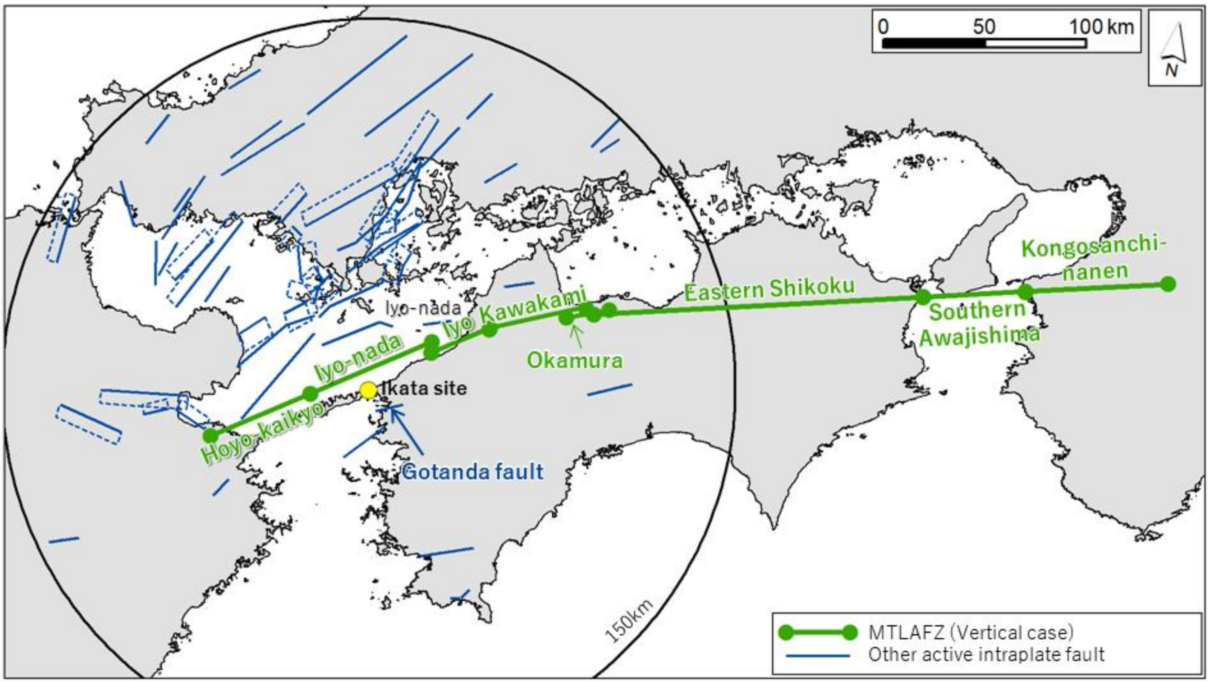


Fig. 4 Source fault distribution of active intraplate faults

Table 3 Basis for segmentation of the MTLAFZ

Segment		Hoyo-kaikyo		Iyo-nada		Iyo		Kawa kami		Okamura		East of Ishizuchi-Sanmyaku-Hokuen
Segment boundary			Misaki-oki		Kushi-oki		Shige nobu		Saijyo		Niihama	
Earthquake segment	Historical record	September 1, 1596?				September 1, 1596			September 1-5, 1596? (No record of earthquake damage)			
Behavioral segment	Latest faulting event	16th century	No Data			16th century						
	previous	About 2500 years ago	No Data			8th century – 1th century				About 3000 years ago		About 2000 years ago
Geometric segment	Dimension of step	none	4km	1km (Ikata-oki)	4km	none	5km	1km (Sakuragi)	3km	none	2km	none
	Sedimentary basin to the top of the seismogenic layer	none	existence	none	existence	none	existence	none	existence	none	unknown	none
Ohter	Slip rate (strike-slip)	No Data				1-4mm/yr			–	5mm/yr >		
	Displacement (strike-slip)	No Data				2-4m			–	5m >		
	Fault type	Strike-slip fault with normal fault component										Strike-slip fault with reverse fault component
	Stress field	Transition field from strike-slip field to tensile field										Strike-slip field including compressive component
	R/S boundary※1 and Active fault relationship	Mismatch	Match			Match?			Mismatch			
	Iz/S boundary※2 and Active fault relationship	–	Mismatch					Partial match	Mismatch			Match
Comparison with previous segmentation (After Nanayama et al.[15])	Nanayama et al.[15]	Almost match	Almost match	Almost match	Almost match	Almost match	–	–	–	–	–	–
	HERP[17]	–	Almost match	Not classified by Kushi-oki and Shigenobu					Match	Match	Match	Match
	HERP[18]	Extended to the west	Match	Not classified by Kushi-oki			Almost match	Match	Match	Match	Match	Match
	Yoshioka et al.[19]	Almost match	Almost match	Further subdivisions	Almost match	Almost match	Almost match	Further subdivisions	Match	Match	Match	Further subdivisions

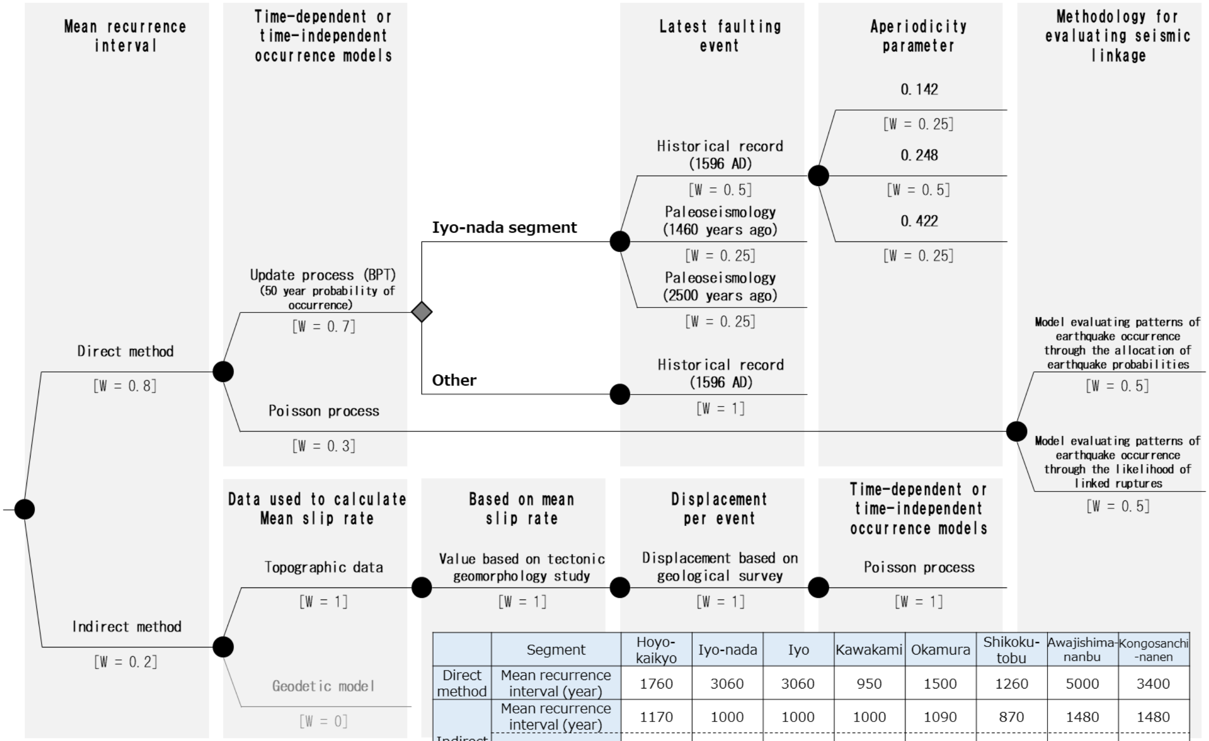
*1 R/S boundary: Boundary between the Ryoke granite and the Sambagawa metamorphic rocks,
*2 Iz/S boundary: Boundary between the Izumi fault group and the Sambagawa metamorphic rocks

(2) Modeling the earthquake magnitude

The evaluation parameter for magnitude of MTLAFZ earthquakes, which are set with specific seismic source fault planes, is a choice of magnitude prediction equations. We therefore discussed prediction equations based on fault length or fault area (Fig. 3a). Moreover, for the long fault of the MTLAFZ, we took the magnitude evaluation methodology of linked earthquakes into consideration and set the fault dip angle as an evaluation parameter as mentioned previously. For the eight segments making up the MTLAFZ (Fig. 4), we had to calculate earthquake magnitudes for cases ranging from a single segment rupturing to all segments rupturing together. For the magnitude evaluation methodology of linked multi-segment earthquakes, we set a branch for the approach calculating seismic moment from the total length or area of the fault and another branch for the approach calculating seismic moment from the length or area of individual segments regardless of their linkage. According to Tsutsumi and Goto[20], the MTLAFZ has surface displacements similar to characteristic earthquakes based on direct displacement distribution data from the past several earthquakes. In light of these, we judged that there was no difference in certainty of these two branches and set the weights equally (0.5:0.5). The parameters used to calculate the earthquake magnitude are fault length and fault area. Although the physical correspondence with seismic moment is clearer when fault area is used, it requires accurate data on fault width (depth and dip at the bottom of the fault rupture region) in addition to fault length. Since detailed data on fault width have been obtained for the MTLAFZ based on many surveys that have been conducted there, the fault area was at the center of the body of opinions. However, considering the uncertainty inherent in the fault width, we judged the weights for the fault length and fault area to be 0.3:0.7 as parameters for calculating magnitude. For magnitude prediction equations, we set branches for several magnitude prediction equations obtained from earthquakes around the world, based on the policy of treating the variability in magnitude as epistemic uncertainty. For prediction equations calculated based on fault length, we exhaustively studied various equations and assigned greater importance to the ability to estimate magnitude based on the surface fault length and the applicable range size across the entire length of the MTLAFZ. Hence, we set the weight of the equation by Wells and Coppersmith[21)] to 1. Additionally, for prediction equations calculated based on fault area, we used three branches for the following: the three-stage equation that uses either Somerville et al.[22)], Irikura and Miyake[23)], or Murotani et al.[24)] depending on the fault area; the equation by Leonard[25)], which had been widely used in SSHAC and other projects worldwide; and the equation by Wells and Coppersmith[21)], which had also been selected as the equation based on fault length discussed above. Here, the three-stage equation makes it possible to express that the stage of the scaling law changes depending on whether the fault width and displacement are saturated. Considering the three-stage equation's extensive use in Japan and taking into account that the entire length of MTLAFZ corresponds to its third stage with saturated fault width and displacement, the three-stage equation was judged as the center of the body of opinions. We also judged that the other remaining branches are equally likely and set the weights of each equation to 0.5:0.25:0.25. For the fault dip angle, after confirming that there is no data supporting a dip south, we set one branch as vertical, which is typical for strike-slip faults, and another as dipping north, which aligns with MTL as a geological boundary. From the perspective of technically defensible interpretations (TDI), we judged that there was no difference in their likelihoods and set the weight equally (0.5: 0.5). Based on the above models, the magnitudes from the case when the Iyo-nada Segment in front of the Ikata site alone ruptures to the case when all segments rupture together range from Mw 6.9 to Mw 8.1.

(3) Modeling the probability of occurrence

The evaluation parameters for the probability of occurrence of earthquakes with set specific seismic source fault planes are the mean recurrence interval, the time-dependent or time-independent occurrence models (update process (Brownian Passage Time (BPT) distribution) or Poisson process), the elapsed time since the latest faulting event, the aperiodicity parameter, and the methodology for evaluating seismic linkage (Fig. 3a). In particular, the probability of occurrence of MTLAFZ earthquakes was considered to have a particularly large impact on seismic hazards since the early stages of the project; hence, intensive discussions were carried out to diligently develop its model. The logic tree consists of a large number of evaluation parameter branches: methodology for evaluating mean recurrence interval, mean slip rate, displacement per event, time-dependent or time-independent occurrence models, elapsed time since the latest faulting event, aperiodicity parameter, and methodology for evaluating seismic linkage (Fig. 5). There are two methodologies for evaluating mean recurrence interval: the direct method using faulting history obtained from geological surveys (950 to 5000 years) and the indirect method calculated from mean slip rate and displacement per event (870 to 1480 years). Since there was plenty of direct data on the faulting history of MTLAFZ, it was clear that the direct method was at the center of the body of opinions. We also judged that the indirect method based on indirect data should be given a small weight, and set their weights to 0.8:0.2. For the mean slip rate used in the indirect method, one branch is the topographic data to derive mean slip rate using tectonic geomorphology surveys and another branch is the geodetic model to derive mean slip rate indirectly through a model based on observations of crustal deformation. Because it was difficult to get an accurate estimate through a geodetic model for the MTLAFZ, which has other active faults running parallel to it, a weight of 1 was set for topographic data based on tectonic geomorphology surveys. The time-dependent or time-independent occurrence models has two branches: the update process (BPT distribution), which is able to reflect information on the elapsed time since the latest faulting event taken from geological surveys and historical records, in the probability of occurrence, and the Poisson process which calculates the probability of occurrence by using only the mean recurrence interval. When the mean recurrence interval is obtained by the direct method, the former should be given greater weight as the center of the body of opinions because there is abundant data on faulting history that includes the latest faulting event of the MTLAFZ. However, in view of the lack of direct faulting history data on the Iyo-nada Segment offshore of the Ikata site, we judged the weights for the update process (BPT distribution) and Poisson process



	Segment	Hoyo-kaikyo	Iyo-nada	Iyo	Kawakami	Okamura	Shikoku-tobu	Awajishima-nanbu	Kongosanchi-nanen
Direct method	Mean recurrence interval (year)	1760	3060	3060	950	1500	1260	5000	3400
Indirect method	Mean recurrence interval (year)	1170	1000	1000	1000	1090	870	1480	1480
	Slip rate(mm/yr)	3	2.5	2.5	2.5	5.5	7.5	2.7	2.7
	Displacement per event(m)	3.5	2.5	2.5	2.5	6.0	6.5	4.0	4.0

Fig. 5 Logic tree of the probability of occurrence on the MTLAFZ

to be 0.7:0.3. On the other hand, when the mean recurrence interval is obtained by the indirect method, only the Poisson process branch was set with a weight of 1 since data on the latest faulting event cannot be set. For the latest faulting event at the Iyo-nada Segment, we set three branches: 1596 when a rupture was believed to have developed until the fault at the Iyo-nada Sea from the Keicho-Iyo Earthquake, 1460 years ago, and 2500 years ago, which are based on boring surveys of the western edge of the Iyo Segment to the east. Although an earthquake certainly occurred at Iyo and Bungo in 1596, historical records and paleo-earthquake data are insufficient. Hence, we judged the center of the body of opinions to be 1596 and considered the other branches based on boring survey results as equally likely, setting the respective weights to 0.5:0.25:0.25. For the latest faulting event at segments other than the Iyo-nada Segment, many trench surveys at the Iyo to Eastern Shikoku segments and at the Hoyo-kaikyo segment support the year 1596. Moreover, in view of the relatively small impact of distant segments on seismic hazard, we decided to collectively consider the latest faulting event as 1596. For the variability of recurrence intervals, we used the methodology utilizing Bayesian prediction by Nomura et al.[26)] to make new calculations of variabilities and weights of the MTLAFZ faulting history, and set the weights of 0.25:0.5:0.25 to branches 0.142, 0.248, and 0.422, respectively. Based on the above models, the 50-year probability of occurrence at the Iyo-nada Segment ranges from nearly 0 to a maximum of around 0.05. Additionally, for the methodology for evaluating seismic linkage, we set branches for a model evaluating patterns of earthquake occurrence through the allocation of earthquake probabilities, which is the latest methodology for active intraplate faults given by HERP[27)], (Table 4) and a model evaluating patterns of earthquake occurrence through the likelihood of linked ruptures, which was our new proposal with the aim of applying it to MTLAFZ earthquakes and the Nankai Trough Megathrust Earthquakes based on the Working Group on California Earthquake Probabilities[28)] and other studies, and set the weights equally for both models (0.5:0.5). Through this model, approximately 6000 cases of single/linked rupture patterns were assumed through a combination of 36 different seismic sources, from the case in which the eight segments rupture alone to the case in which all rupture together.

Table 4 Concept of the methodology for earthquake linkage evaluation

Model	Assumed scenario (with two source) No.	Source A	Source B	Evaluation Method
Model evaluating patterns of earthquake occurrence through the allocation of earthquake probabilities	1	A		・Model applied to the MTLAFZ earthquakes. ・The seismic hazard is evaluated by assuming that at least one of the three earthquakes will occur during the evaluation period (the occurrence of the three earthquakes is evaluated with a single hazard curve). ・The probability of occurrence is set for each of the three earthquakes.
			B	
		AB		
Model evaluating patterns of earthquake occurrence through the likelihood of linked ruptures	1	(A do not rupture)	(B do not rupture)	・Model applied to the MTLAFZ earthquakes and Nankai Trough Megathrust Earthquakes. ・The seismic hazard is evaluated assuming that one of the scenarios occurs during the evaluation period (add up the hazard curves for each scenario). ・The probability of occurrence of source A and source B is set. ・The probability of occurrence of linked rupture pattern (No.5,6) is evaluated based on the probability* that adjacent source will be linked if a rupture occurs at each source. *The probability of linkage is assumed to be equally distributed.
	2	A	(B do not rupture)	
	3	(A do not rupture)	B	
	4	A	B	
	5	AB (A→B)		
	6	AB (B→A)		
model evaluating patterns of earthquake occurrence through historical records	1	A		・Model applied to Nankai Trough Megathrust Earthquakes. ・If an earthquake occurs during the evaluation period, the seismic hazard is evaluated for one of the scenarios. (The hazard curves for each scenario are weighted averaged.) ・The probability of occurrence is set to one value for the entire fault zone (source A and source B).
	2		B	
	3	A	B	
	4	AB		

4.1.2 SSC models of other active intraplate fault earthquakes

(1) Modeling the location and geometry

The structure of the logic tree for location and geometry for other active intraplate fault earthquakes followed the model for MTLAFZ earthquakes, except that segmentation was unnecessary because they are not long active faults. For other active intraplate fault earthquakes, to consider the impact on seismic hazard, we modeled the source faults corresponding to active intraplate faults located within a 150 km radius of the Ikata site (Fig. 4) on the active fault distribution map (Fig. 1) in accordance with previous studies. In addition, the Gotanda fault shown in the book edited by the Research Group for Active Faults of Japan[29)] is the closest to the Ikata site and has been identified as a presumed active fault based on tectonic geomorphology, although no fault was found at outcrops on the estimated fault line. Hence, we added a parameter for whether an active fault exists or not. Afterward, the SSC Team performed photographic interpretation and other work to reach a conclusion that there was not enough information to make a determination, and set the weights for "active fault" and "non-active fault" to 0.5:0.5. Furthermore, we adopted a depth of 15 km for the fault rupture region bottom and source fault bottom of the Gotanda fault located in the northwestern part of Shikoku, where seismic source distribution is shallow, according to seismicity data such as D90 and crustal heat flow.

(2) Modeling the magnitude

The evaluation parameters and basic structure of the logic tree for magnitude of other active intraplate fault earthquakes was the same as those of the MTLAFZ, except that the magnitude evaluation methodology for linked earthquakes was not required. However, for short fault lengths, we decided to set magnitudes directly because of the difficulty of accurately estimating magnitudes using magnitude prediction equations. We judged faults that are less than 15 km long as short faults based on the concept of short active faults by the HERP[14)]. For the Gotanda fault, a 2-km long short active fault closest to the

Ikata site, we set three branches: Mw 6.2, based on the finding by Toda and Ishimura[30] that even fairly small earthquakes of around M 6 are associated with earthquake faults of less than 5 km in length; Mw 6.5, which corresponds to the minimum magnitude occurring in a short active fault according to Shimazaki[31]; and Mw 6.9, which corresponds to the maximum magnitude occurring in a short active fault according to Shimazaki[32]. Based on findings that the rate of occurrence of surface ruptures increases sharply at Mw 6.5, and although the results are unclear, we judged Mw 6.5 to be the center of the body of opinions. Furthermore, we judged some weight should be given to other branches of smaller magnitudes and larger magnitudes, and set the weights to 0.2:0.6:0.2. We also confirmed that other active intraplate faults farther away than the Gotanda fault have little effect on seismic hazard and set a weight of 1 for a representative value of Mw 6.6, corresponding to the maximum magnitude of earthquakes with unclear surface ruptures, with the exception of the 2000 Tottori Earthquake.

(3) Modeling the probability of occurrence

The structure of the logic tree for probability of occurrence of other active intraplate fault earthquakes followed the model for MTLAFZ earthquakes. For the methodology for evaluating the mean recurrence interval, considering that other active intraplate fault earthquakes have little effect on seismic hazard, we calculated the mean recurrence interval using the direct method if faulting history is available and the indirect method for faults whose faulting history is unknown. Similarly, for the temporal model of earthquake recurrence, we used the update process (BPT distribution) if the history of the latest faulting event is available and the Poisson process if there is no history of the latest faulting event. To calculate the mean recurrence interval using the indirect method, in the absence of direct data on mean slip rate such as those for the MTLAFZ, we uniformly set the mean slip rate based on the level of activity of active faults[33] and, in principle, determined the displacement per event from the relationship between fault length and unit displacement based on Matsuda[34] and the directly set magnitudes. For the variability of recurrence intervals, we referred to the value obtained from data on faulting history of 23 active faults in Japan by Kumamoto and Hamada[35] and set the weight to 1 for a representative value of 0.5.

4.1.3 SSC model of the Nankai Trough Megathrust Earthquakes

(1) Modeling the location and geometry

The parameters comprising the logic tree for location and geometry of the Nankai Trough Megathrust Earthquakes are the assumed focal regions and the depths of the top and bottom of fault planes. For the assumed focal regions, we referred to recent findings to divide the Nankai Trough into four regions in the east–west direction, namely (1) Hyuga-nada, (2) Nankai, (3) Tonankai, and (4) Tokai from west to east, based on a model by HERP[36] and set the Nankai Trough focal regions (Fig. 6). Since this is consistent with past source models and seismicity is highly reliable, we judged that it was unnecessary to set other branches. The assumed focal regions were further divided into the central zone that has conventionally been considered as a seismogenic zone due to the locking of plates, the shallow zone

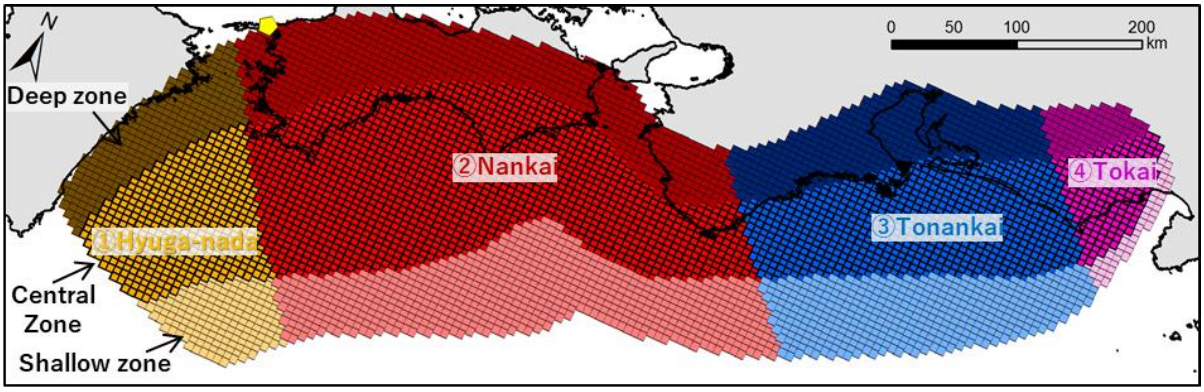


Fig. 6 Assumed focal regions and fault planes of the Nankai Trough Megathrust Earthquakes

near the trough axis that had slipped by a large amount during the 2011-off-the-Pacific-coast-of-Tohoku Earthquake, and the deep zone considered to be a region where the plates have locked to some extent because deep-zone low-frequency earthquakes have been observed (Fig. 6). For the top of fault planes, we set the top of the central zone as a branch with a weight of 1. Based on Japan's Cabinet Office's[37)] definition of the shallow zone as an area that has a possibility of causing large tsunamis although the likelihood of strong ground motions is low, we judged that for strong ground motions that should be considered at the Ikata site, the shallow zone does not contribute to the magnitude. For the bottom of fault planes, we set branches for the central zone bottom and deep zone bottom and set the weights to 0.9 for the former and 0.1 for the latter, because although there is no data to positively support the occurrence of M 9-class mega thrust earthquakes at the Nankai Trough, we cannot completely rule out the possibility of a strong ground motion occurring at the deep zone. The weight of 0.1 is the interpretation for setting the end of the range of a very small number of opinions for the physically or geologically possible, although there is no supporting data.

(2) Modeling the magnitude

The parameter comprising the logic tree for magnitude of the Nankai Trough Megathrust Earthquakes are the magnitude prediction equation. For the assumed source fault planes of the Nankai Trough Megathrust Earthquakes, we used the latest model, which approximates the vast focal region by dividing it into small fault planes with 5-km grids (Fig. 6). Judging that the reliability of this model is high, we used the fault area alone as a parameter to calculate the magnitude. Similar to the MTLAFZ, we set branches for several magnitude prediction equations based on the policy of treating the variability in magnitude as epistemic uncertainty, and selected magnitude prediction equations based on three grounds: that it has a wide range of application with the ability to predict from M 7 to M 9-class earthquakes, that it is based on datasets that include the 2011-off-the-Pacific-coast-of-Tohoku Earthquake and other subduction-zone earthquakes in Japan, and that it is formulated to evaluate strong ground motions. We set three branches: bilinear models that can take into account the fault width saturation by using equations by Murotani et al.[38)] or by Tajima et al.[39)] depending on the fault area; the equation by Skarlatoudis et al.[40)], which matches well with the magnitude of past earthquakes at Nankai Trough; and the equation by Allen and Hayes[41)], which has a wide range of applications although it tends to give larger magnitudes than those of past earthquakes at the Nankai Trough, and gave equal weights (1/3) to each with the view of epistemically addressing the uncertainty of magnitude prediction. Based on the above models, the magnitudes for the Nankai Trough Megathrust Earthquakes from the case of a partial rupture up to the case of a full rupture of the vast focal region range from Mw 7.7 to Mw 9.0.

(3) Modeling the probability of occurrence

The parameters comprising the logic tree for probability of occurrence of the Nankai Trough Megathrust Earthquakes are the mean recurrence interval, the elapsed time since the latest faulting event, the time-dependent or time-independent occurrence models, the aperiodicity parameter, and the methodology for evaluating seismic linkage. The mean recurrence interval was calculated based on past historical records. We set two branches: one branch for the highly reliable period from 1361, considering the high possibility that earthquakes before 1361 have been overlooked due to a lack of historical records, and another branch for the period from 684, which is the entire period for which there are historical records with the view of utilizing data over longer time periods. We judged the highly reliable post-1361 period as the center of the body of opinions and set the weights to 0.7:0.3. We set the latest faulting events for the Nankai, Tonankai, and Tokai regions to 1946, 1944, and 1854 respectively based on historical records, and set the Hyuga-nada region to unknown. For the time-dependent or time-independent occurrence models, we gave a weight of 1 to the update process (BPT distribution), which is able to reflect information on the known latest faulting events of the Nankai, Tonankai, and Tokai regions in the probability of occurrence. For the Hyuga-nada region whose latest faulting event is unknown, we set only the Poisson process branch. We calculated the aperiodicity parameter independently based on the set historical record, resulting in 0.18 when using historical record from 1361 and 0.35 when using historical record from 684. Based on the above models, the 50-year probability of occurrence of the four focal regions ranges from 0.2 to around 0.9. Additionally, for the methodology to evaluate seismic linkage, similar to the previously discussed MTLAFZ, we set one branch for a model evaluating patterns of earthquake occurrence through the likelihood of linked ruptures (Table 4). Another branch was a model evaluating patterns of earthquake occurrence through historical records (Table 4), which sets a single probability of occurrence for the entire Nankai Trough and gave weights for earthquake patterns based on the approach considering various earthquake patterns for the Nankai Trough Megathrust Earthquakes by HERP[36]. The weights were set equally for both models (0.5:0.5). Through this model, 60 cases of single/linked rupture patterns were assumed through a combination of 10 different focal regions, ranging from the case where four focal regions rupture alone to cases where all focal regions rupture together.

4.2 SSC models of earthquakes with no set earthquake source fault planes

4.2.1 SSC models of blind earthquakes in landward plates

(1) Modeling the location and geometry

The evaluation parameter for location and geometry of earthquakes with no set earthquake source fault planes is the regional division (Fig. 3b). In particular, the parameters for blind earthquakes in landward plates are the depths of the seismogenic layer top/bottom and the layout of seismic sources, in addition to the regional division setting. For the regional division setting, we set one branch with regional division and another without regional division. In the branch with regional division, the area was first divided into multiple extensive regions that may be regarded as having uniform seismicity and then modeled with uniformly distributed seismic sources within each region; we then used the seismotectonic province map by HERP[36), 42)] as a basis and set a region within 15 km around the MTLAFZ (equivalent to the thickness of the seismogenic layer), based on the concept that the MTLAFZ is not a seismotectonic

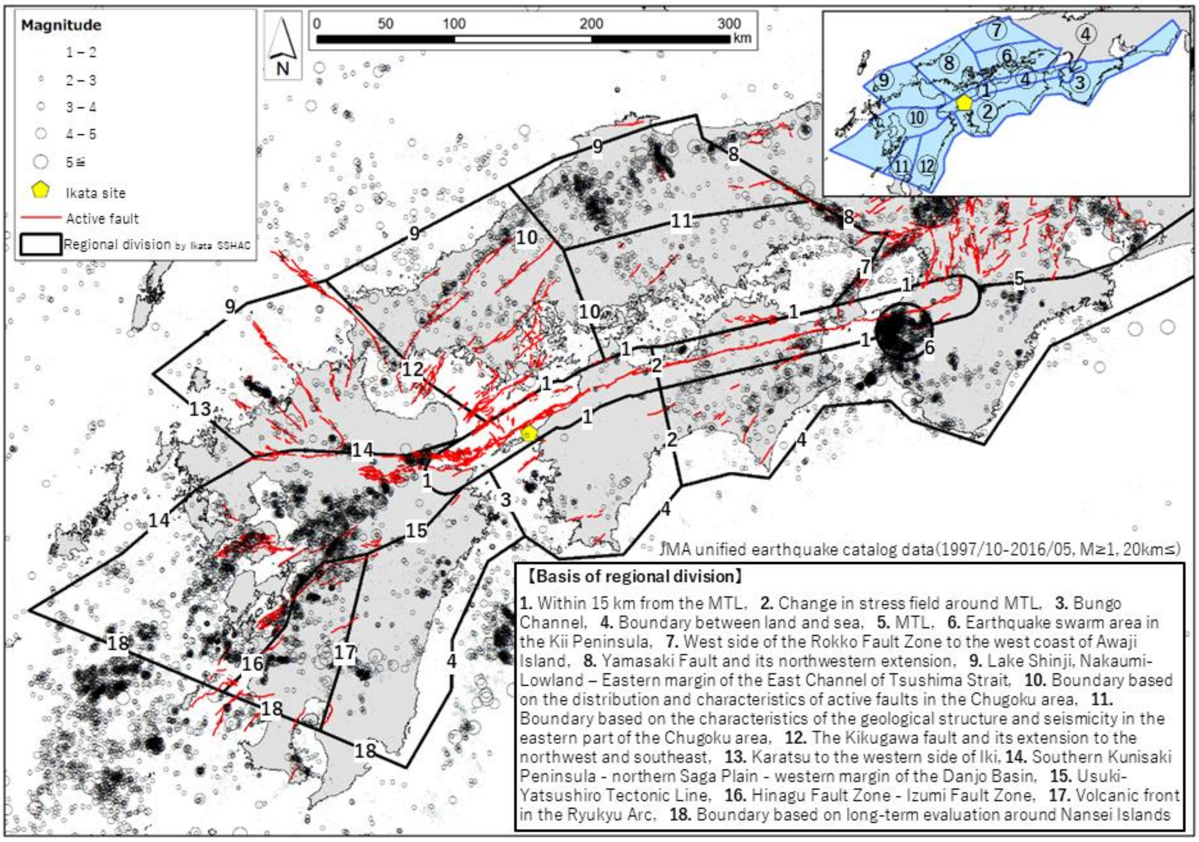


Fig. 7 Regional division map of blind earthquakes in landward plates

province boundary by Kumamoto et al.[43] and the concept that seismicities in and around the MTLAFZ are similar to characteristic earthquakes by Ishibe and Shimazaki[44] (Fig. 7). Also, considering that the MTLAFZ passes in the closest of the Ikata site, we judged that classifying the Ikata site as belonging to the zone of influence of the MTLAFZ is appropriate, so we did not create branches for existing seismotectonic province maps using the MTLAFZ as a boundary (e.g., Kakimi et al.[45]). On the other hand, for the branch without regional division, we referred to the concept of smoothed seismicity by Frankel[46] and divided the range of the model of other active intraplate fault earthquakes plus the area within a 150-km radius from the site into 0.1° meshes along the latitude-longitude directions, and then adopted a method of smoothing seismicity using a Gaussian distribution with a correlation distance of 25 km. To set the weights, we considered the characteristics of each methodology: although seismotectonic differences of each region can be considered with the use of regional divisions, there is arbitrariness in the setting of division boundaries, whereas the problem of arbitrariness in division boundaries is resolved if regional divisions are not used but the differences in seismogenic mechanism of each location cannot be reflected. We therefore set the weights equally (0.5:0.5). For the depths of the seismogenic layer top/bottom, we set representative values of 2 km/18 km with a weight of 1 in consideration of the fact that the seismogenic layer encompasses a wide area and that its impact on seismic hazard is small, based on findings by HERP[36), 47]. For layout of seismic sources, we decided to set planar positions of seismic sources uniformly for each region since we cannot predict the characteristic location of seismic sources beforehand and considered it appropriate to uniformly distribute seismic sources.

(2) Modeling the magnitude

The evaluation parameters for magnitude of earthquakes with no set earthquake source fault planes are the maximum and minimum magnitudes (Fig. 3b). We set a common minimum magnitude of Mw 5.0 for the three seismic sources, to account for the minimum magnitude that causes structural damage to large buildings. For the maximum magnitude of blind earthquakes in landward plates, we set three branches: Mw 6.5, the magnitude at which the likelihood of surface ruptures sharply increases[32), 48]; Mw 6.6, which corresponds to the maximum magnitude of earthquakes with earthquakes without specific source faults according to Shimazaki[32]; and Mw 6.8, the magnitude of the 2000 Tottori Earthquake, for which there have been differences in opinions on whether it produced surface ruptures. For the case with regional division, we set weights based on the finding by Toda[49] that there are few small-magnitude faults in the closest of major fault lines where there are efficient strain releases across a wide area. We gave a large weight to Mw 6.5 for the region on the outer zone side along the Nankai Trough where simple stress is accumulated and released, and gave a large weight to Mw 6.8 for the region on the inner zone side far from the Nankai Trough where many immature active faults are distributed. Since the Ikata site is in between these and belongs to a region undergoing efficient strain release due to the mature MTLAFZ, we judged that the center of the body of opinions is Mw 6.6 and considered the other branches as equally likely, setting the respective weights of Mw 6.5, Mw 6.6, Mw 6.8 to 0.25:0.5:0.25. For the case without regional division, we set the whole area in the same way as the region that includes the Ikata site in view of their impact on seismic hazard.

(3) Modeling the probability of occurrence

The evaluation parameters for the probability of occurrence of blind earthquakes in landward plates are the frequency of occurrence (G–R law) and the time-independent occurrence model (Poisson process) (Fig. 3b). For the earthquake catalog used to calculate the frequency of occurrence, we used the Japan Meteorological Agency (JMA) unified earthquake catalog data for earthquakes $M \geq 1.0$ in the period from October 1, 1997 to May 31, 2016, which was declustered using the method by Reasenberg[50]. Compared with the results using other earthquake catalogs with long observation periods and multiple declustering methods, we found no significant difference in frequency distributions by magnitude between catalogs and confirmed that the catalog was adequate as source data for analysis based on the seismic source distribution and number of earthquakes after declustering, and judged that it was unnecessary to set other branches. We identified earthquakes that occurred less than 20 km deep within the region and considered them as earthquakes in landward plates, and treated other earthquakes as earthquakes that occurred in the Philippine Sea plate. In addition, the G–R law calculation method assumes that the frequency distribution by magnitude based on the earthquake catalog follows the G–R law. We set the frequency of occurrence for each magnitude by calculating a- and b-values using the method of Utsu[51)]. Here, we set branches for the minimum magnitude Mc, which is important in the G–R law calculation, using Mc = 2.0 and Mc = 3.0 with equal weights given to each (0.5:0.5). For the time-dependent or time-independent occurrence model, based on the thinking that the Poisson process is generally used as the frequency of earthquake occurrence does not change across the temporal axis because of the nature of evaluating earthquakes distributed over a certain range of area collectively rather than evaluating individual faults, we judged that it was unnecessary to set other branches. Table 5 shows the results of setting the G–R law near the Ikata site.

Table 5 G–R law for blind earthquakes in landward plates and the Philippine Sea Plate

Source	Regional division setting	Minimum magnitude Mc	a value	b value	Number of earthquakes above Mc
Blind earthquakes in landward plates	Regional division*1	Mc=2.0	2.354	1.049	36
		Mc=3.0	—	—	4※2
	Without regional division	Mc=2.0	3.811	0.894	2,108
		Mc=3.0	4.049	0.978	262
Blind earthquakes in the Philippine Sea Plate	Regional division*1	Mc=3.0	4.100	0.825	843
		Mc=4.0	4.621	0.958	123
	Without regional division	Mc=3.0	3.952	0.774	851
		Mc=4.0	4.544	0.930	134

*1 Indicates values for the region that includes the Ikata site
*2 Values for Mc = 2.0 only were adopted since the number of earthquakes is less than 10 for Mc = 3.0.

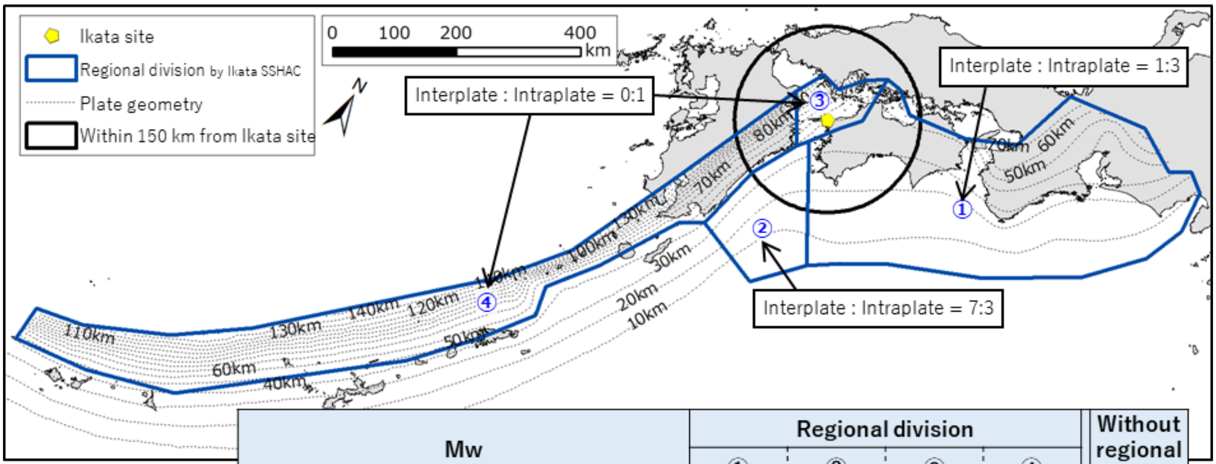
4.2.2 SSC models of blind earthquakes in the Philippine Sea Plate

(1) Modeling the location and geometry

The parameters comprising the logic tree for location and geometry of blind earthquakes in the Philippine Sea Plate are the regional division setting and the layout of seismic sources, which are similar to blind earthquakes in landward plates, as well as the plate geometry and the ratio of interplate to intraplate earthquakes. For the regional division setting, we set equal weights (0.5:0.5) to the branches with and without regional division, similar to blind earthquakes in landward plates. For the branch with regional division, we adopted the regional division set by HERP[36)] (Fig. 8) after verifying the adequacy of its evidence. For the branch without regional division, the mesh division was identical to blind earthquakes in landward plates described above. For the setting of seismic sources, we decided to set planar positions of seismic sources uniformly for each region since we cannot predict the characteristic location of seismic sources beforehand, similar to blind earthquakes in landward plates. For the plate geometry, since we adopted the geometries proposed by HERP[36)] for regional divisions, we decided to use HERP[36)] plate geometries as well. Here, the depth of the Philippine Sea plate directly below the Ikata site is approximately 41 km. For the ratio of interplate to intraplate earthquakes, after verifying that there was no reason to change the ratios from the focal mechanism solution around the Ikata site, we adopted the ratios set by HERP[36)] for each region (Fig. 8). Here, the ratio of the region directly below the Ikata site was 0:1. Since the earthquake hazard is particularly affected by seismic sources with epicenters located within about 60 km from the site, this ratio was adopted for the whole area for the case without regional division.

(2) Modeling the magnitude

The parameters for magnitude of blind earthquakes in the Philippine Sea Plate are the maximum



Mw		Regional division ①	Regional division ②	Regional division ③	Regional division ④	Without regional division
Maximum magnitude of intraplate earthquake	Historical records	7.3	7.2	7.4	7.6	7.4
	Results of reexamining historical records	7.0	7.4	7.0	7.3	7.0
Maximum magnitude of interplate earthquake		8.0	7.6	No occurrence	No occurrence	No occurrence

Fig. 8 Regional division map of blind earthquakes in the Philippine Sea Plate

magnitude of intraplate earthquakes and maximum magnitude of interplate earthquakes. For branches on maximum magnitude of intraplate earthquakes, we set one branch that uses historical records of magnitudes and another branch that uses the results of reexamining historical records of magnitudes through seismic intensity inversion (e.g., Kanda et al.[52)]). For their weights, we considered the second to have better reliability because of the additional analytical studies of the dataset and judged it to be the center of body of opinions, setting the weights to 0.3:0.7. Additionally, for the maximum magnitude of intraplate earthquakes, we focused on the 1911 Amami-Oshima-Kinkai-Earthquake (M 8.0), which is considered to be the largest in the region under consideration based on records of destructive earthquakes by Usami et al[53)]. The results showed that this earthquake is highly likely to be an interplate earthquake with a shallow hypocenter. Hence, since it is physically impossible for M 8-class intraplate earthquakes to occur in the region near the Ikata site, where the slab is thin and curved, we decided to not consider it as an earthquake occurring within the Philippine Sea Plate. For the maximum magnitude of interplate earthquakes, we set the maximum magnitude to be lower than the magnitude of large earthquakes recurring in each region. Based on the above, for the maximum magnitude of intraplate earthquakes in the region directly below the Ikata site, we gave weights of 0.3:0.7 to branches Mw 7.4:Mw 7.0, as well as determined that interplate earthquakes of these magnitudes will not occur. For the case without regional division, we assumed that the setting for the region directly under the site, which has a large impact on earthquake hazards at the Ikata site, is the same for the whole area.

(3) Modeling the probability of occurrence

The parameters comprising the logic tree for probability of occurrence of blind earthquakes in the Philippine Sea Plate are similar to those of blind earthquakes in landward plates: the earthquake catalog, the frequency of occurrence (G–R law), and the time-independent occurrence model (Poisson process). The difference is that the values of the minimum magnitude Mc branches were set to Mc = 3.0 and Mc = 4.0, although the weights were similarly set to be equal (0.5:0.5). Note that in calculating the frequency of occurrence, we calculated the G–R law from the frequency distribution by magnitude based on the seismicity within each region, and then assigned the frequency of occurrence according to the ratio of interplate to intraplate earthquakes. Table 5 shows the G–R law settings near the Ikata site.

4.2.3 SSC models of earthquakes smaller than the characteristic magnitude of active intraplate faults

(1) Modeling the location and geometry

The evaluation parameter for location and geometry of earthquakes smaller than the characteristic magnitude of active intraplate faults is the layout of seismic sources. After confirming that these earthquakes have almost no impact on seismic hazard except for earthquakes occurring at the Iyo-nada Segment of the MTLAFZ closest to the Ikata site, we decided to include only earthquakes smaller than the characteristic magnitude occurring at the Iyo-nada Segment. In the logic tree, we laid out seismic sources uniformly in the fault plane of the Iyo-nada Segment.

(2) Modeling the magnitude and probability of occurrence

The parameters comprising the logic tree for magnitude and probability of occurrence of earthquakes smaller than the characteristic magnitude in the Iyo-nada Segment are the maximum magnitude, frequency of occurrence (G–R law), and time-independent occurrence model (Poisson process). For the modeling, the MTLAFZ distribution shape is a typical mature fault structure, and so we considered it appropriate to apply the characteristic earthquake model by Wesnousky[54)]. In light of the maturity of this active fault, we judged that it was unnecessary to set other branches based on the characteristic earthquake model.

We referred to the fact that in comparing characteristic earthquakes and other earthquakes, the maximum magnitude M of the latter is generally smaller by 1–2 than the former[44)], and set the maximum magnitude M of earthquakes smaller than the characteristic magnitude in the Iyo-nada Segment to be smaller by 1 than the magnitude of characteristic earthquakes. Considering that the characteristic magnitude at Iyo-nada Segment ranges from Mw 7.0 to Mw 7.3 in modeling the magnitude for MTLAFZ earthquakes described above, we adopted Mw 6.3 as the maximum magnitude of earthquakes smaller than the characteristic magnitude, which is 1 less than the upper limit of Mw 7.3. To determine the frequency of occurrence with the G–R law based on the characteristic earthquake model, we considered the frequency of the maximum magnitude earthquake to be the same as the frequency of the characteristic earthquake (mean recurrence interval at the Iyo-nada Segment)[54)], and set the frequency of occurrence for each magnitude assuming that earthquakes less than the maximum magnitude follow the G–R law with a b-value of 1. This model does not depend on earthquake catalogs, so double counting of seismicity from models of blind earthquakes in landward plates based on earthquake catalogs does not occur. For the time-independent occurrence model, we used the Poisson process as in the case of blind earthquakes in landward plates and in the Philippine Sea Plate.

5. DISCUSSIONS ON THE DEVELOPED SSC MODEL

5.1 Comparison with the HERP Model

The evaluations published by HERP, a government agency that centrally promotes earthquake research, have gained public trust in Japan, and are often incorporated directly into models in typical PSHAs. However, in the process of applying the SSHAC Level 3 Guidelines aimed at capturing the CBR of TDI, overseas advisors repeatedly warned of the bias caused by incorporating the HERP evaluation into our models and asked that we strictly treat the evaluation objectively as a piece of data to avoid bias in developing models.

In this section, we compare the SSC model developed by the Ikata SSHAC Project and the model in the National Seismic Hazard Maps of Japan by HERP[47)] (HERP model). Here, with a view of examining the effectiveness of the process in the SSHAC Level 3 Guidelines, we perform the comparison on the SSC model of the MTLAFZ located in the Iyo-nada Sea (SSHAC model), on which we spent the most time and effort discussing in the Ikata SSHAC Project (Table 6).

We objectively treated the HERP model as one of the most important data and studied it in depth including the basis for its evaluation, in order to capture the CBR of TDI for the SSHAC model used in the PSHA at the Ikata site. The SSHAC model was generally consistent with the HERP model and

Table 6 Comparison of SSHAC and HERP models

Parameter		SSHAC model	HERP model
Location and Geometry	Fault length	54 km (Iyo-nada segment)	88 km (Iyo-nada section)
	Top of the source fault	2 km(1), 3 km(0)	4 km
	Bottom of the source fault	15 km(0.3), 18 km(0.7)	16 km
	Dip angle	Vertical(0.5), North dip(40 deg.) (0.5)	Vertical(1/3), North dip(40N) (2/3)
Magnitude	Parameters used for calculation	Based on fault length(0.3), Based on fault area(0.7)	Single rupt. : Based on fault length Linked rupt. : Based on fault area
	Magnitude prediction equations	Fault length : W&C Fault area : Three-stage equation (0.5), Leonard(0.25), W&C(0.25)	Single rupt. : Matsuda(1975) & Takemura(1990) Linked rupt. : Three-stage equation
Probability of occurrence	Mean recurrence interval	Direct method(3060 years)(0.8), Indirect method(1000 years)(0.2)	3100 years
	Time-dependent or time-independent occurrence models	Direct method : Update process (BPT)(0.7), Poisson process(0.3) Indirect method : Poisson process	Update process (BPT)
	Latest faulting event	AD1596(0.5), 1460 years ago(0.25), 2500 years ago(0.25)	AD1750 (After 17th century - before 19th century)
	Aperiodicity parameter	0.142(0.25), 0.248(0.5), 0.422(0.25)	0.24
	Methodology for evaluating seismic linkage	Model evaluating patterns of earthquake occurrence through the allocation of earthquake probabilities(0.5), Model evaluating patterns of earthquake occurrence through the likelihood of linked ruptures(0.5)	Model evaluating patterns of earthquake occurrence through the allocation of earthquake probabilities

* The number in parentheses indicates the weight.

expressed various uncertainties through more branches (Table 6). For example, with respect to the aperiodicity parameter in the SSHAC model, we set three branches based on results obtained by asking outside experts invited to an open workshop to calculate the aperiodicity parameter based on Bayesian prediction using our independently collected faulting history for each segment of the MTLAFZ, in which the value of the center is nearly the same as the value in the HERP model. While the SSHAC model was a model that captured the CBR of TDI specific to individual sites, the HERP model was a model developed with earthquakes that are considered most likely to occur in Japan in mind. Additionally, although both models have been constructed as a result of discussions by many experts, the HERP model was not constructed by using a well-documented process following strict guidelines as in the SSHAC model. Therefore, the differences between the two models may be attributed to both their difference in purpose and process.

The main parameters of the two models in which there is a clear difference in central values themselves are the fault length, the top of the source fault, the weight of the fault dip angle, and the latest faulting event (Table 6). Here, for the bottom of the source fault, the SSHAC model attached greater importance to including the entire region, which includes the central eastern part of Shikoku as mentioned above, and so with 15 km, does not conflict with the HERP model based on long-term evaluation[18]. First, for fault length in the SSHAC model, whose aim was to conduct a PSHA specific to the Ikata site, the epistemic uncertainty caused by the lack of direct faulting history data on the Iyo-nada Segment offshore of the Ikata site was taken into account by using the step faults at Kushi-oki as a segment boundary. Next, for top of the source fault in the SSHAC model, 2-km and 3-km branches were set based on direct data on the velocity structure at Iyo-nada Sea after considering the 4 km set by the HERP as well. The construction of the model attached greater importance to the availability or unavailability of direct data as a basis for developing the model in order to capture the CBR of TDI. For fault dip angle, the weights of vertical to north dip in the HERP model were 1/3:2/3, based on the long-term evaluation that it is highly likely that the fault is dipping north because there has been no evidence showing the MTLAFZ cutting through the geological boundary of the MTL[18]. On the other hand, in the SSHAC model, we received detailed explanations from outside experts at the open workshops which includes data suggesting that geological boundary faults were being displaced by high-angle faults. The issue was considered further through discussions with the PPRP, whose members included experts familiar with the MTLAFZ. With proper consideration of the opinions of experts aside from those directly involved in model development to capture the CBR of TDI, we judged that the distribution of opposing opinions was evenly matched, with both sides judged to be equally likely. Finally, for latest faulting event, in the HERP model without segmentation at the step faults at Kushi-oki, the parameter was set based on dating that corresponds to the latest faulting event shown in previous studies of reports on trench surveys at continental northwestern Shikoku[55]. On the other hand, for the SSHAC model segmented at the step faults at Kushi-oki, we received detailed briefings in an open workshop on the faulting history and historical records of the MTLAFZ stretching from northwestern Shikoku through the Iyo-nada Sea to Beppu Bay from outside experts, which includes authors of previous studies: the model was developed by appropriately modeling epistemic uncertainty such as the possibility of missing data on direct faulting history or missing historical records. Thus, the SSHAC model went through the process of the SSHAC Level 3 Guidelines to become a highly reliable model that captured the CBR of TDI specific to an individual site.

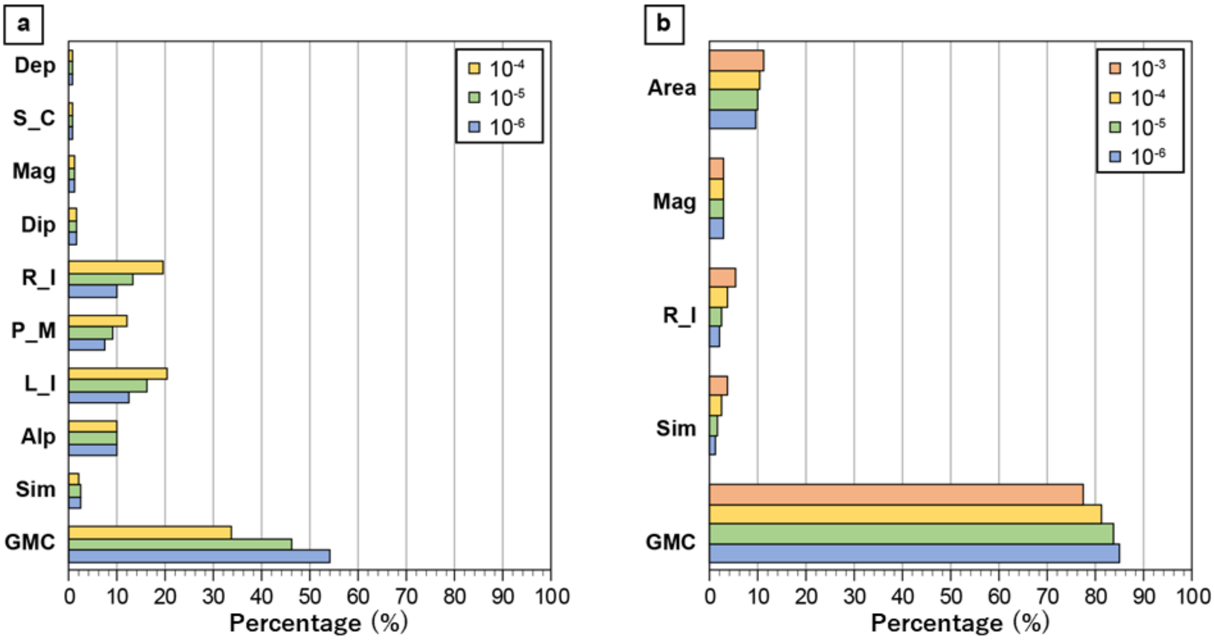
5.2 Discussion on branch parameters with large impacts on seismic hazard

We analyzed the contribution to seismic hazard of each branch parameter for MTLAFZ earthquakes closest to the Ikata site as well as the Nankai Trough Megathrust Earthquakes, which has a high probability of occurrence. Here, we verify the contribution to seismic hazard of each branch parameter in the logic tree using a variance contribution plot, which shows the degree of impact of branch parameters on the PSHA results by means of bar graphs showing ratios of the range of seismic hazard curves of certain parameters to the range of all hazard curves. The more the seismic hazard curves change due to the branches set for a branch parameter, the larger the range of seismic hazard curves for that parameter; and hence, the parameter will be shown with longer bar graphs in the variance contribution plot.

Figure 9(a) shows the variance contribution plot for the case including the Iyo-nada Segment, which has the dominant effect among MTLAFZ earthquakes. For example, for an annual frequency of exceedance of 10^{-4} (yellow in the figure), parameters related to GMC models account for about 33% of the impact on seismic hazards, while parameters related to calculating the probability of occurrence in SSC models (mean recurrence interval, time-dependent or time-independent occurrence model, elapsed time since the latest faulting event, aperiodicity parameter, and methodology for evaluating seismic linkage) account for about 63%. This can be interpreted to mean that the epistemic uncertainty in calculating the probability of occurrence is large, and that investigating the faulting history of the Iyo-nada Segment, for which there is no data by the direct method, will greatly contribute to improving the reliability of seismic hazard estimates. The sedimentary layer for the past several thousand years is thin at the Iyo-nada Sea, making it difficult to investigate faulting history using a paleoseismic approach. We hope that the development of new surveying technologies and further analysis of historical seismiciy will shed light on its latest faulting event. On the other hand, despite the very large epistemic uncertainties and divided expert opinions on parameters related to location and geometry including depth of fault bottom and fault dip angle, and parameters related to magnitude (magnitude evaluation methodology of linked earthquakes, magnitude prediction equation, their impacts on seismic hazards are little. This is because given the geological conditions along the Iyo-nada Segment (54 km long) that is part of the MTLAFZ, which is a long active fault located about 8 km offshore from the Ikata site, ground motion levels at the Ikata site are at nearly peak levels with the Iyo-nada Segment alone so that ground motion levels do not change even with multi-segment linked earthquakes, and because for the epistemic uncertainty of the fault dip angle, there are no faults dipping to the south of the site location.

Figure 9(b) shows the variance contribution plot for the Nankai Trough Megathrust Earthquakes.

Parameters related to GMC models account for about 80% of the overall impact on earthquake hazard while parameters related to SSC models account for less than 20%. The reason for this is that while the probability of occurrence has a large impact in SSC models, the epistemic uncertainty of the probability of occurrence is small because historical records have shown recurring seismic activities since 684 for Nankai Trough Megathrust Earthquakes. In SSC models, the setting for the fault area (setting for the bottom of fault planes) has the largest impact. This is because although previous findings suggest that focal regions are far from the Ikata site to the south, we set a branch to include the deep zone almost directly under the Ikata site in the focal region and gave a weight of 0.1 as the end of the range of body of opinions, in consideration of M 9-class earthquakes such as the 2011-off-the-Pacific-coast-of-Tohoku Earthquake that have exceeded previous records.



(a) MTLAFZ earthquakes (b) Nankai Trough Megathrust Earthquakes

Fig. 9 Variance contribution plot. Representative horizontal ground motion results for a period of 0.02 s are shown. For the abbreviated names in the figure, Dep is the depth of fault bottom, S_C is the magnitude evaluation methodology of linked earthquakes, Mag is the magnitude prediction equation, Dip is the fault dip angle, R_I is the calculation method for mean recurrence interval, P_M is the temporal model of earthquake recurrence, L_I is the latest faulting event, Alp is the recurrence interval variation, Sim is the methodology for earthquake linkage evaluation, GMC is the total impact of ground motion characterization models, and Area is the setting for the fault area. (a) shows the case for the Median Tectonic Line Active Fault Zone earthquakes including the Iyo-nada Segment.

6. CONCLUSIONS

In the area around the Ikata site located in northwestern Shikoku, the expected seismic sources include earthquakes in the long active fault of the MTLAFZ, megathrust earthquakes occurring at plate boundaries known as the Nankai Trough Megathrust Earthquakes, and blind earthquakes in the Philippine Sea Plate such as the Geiyo Earthquake, which makes it essential to conduct a seismic hazard assessment and handle the uncertainties in such an assessment. The Ikata SSHAC Project is the first attempt to use SSHAC Level 3 in Japan. In order to quantitatively evaluate the uncertainties inherent in the natural phenomenon of earthquakes, the SSC Team spent a great deal of time and effort to thoroughly discuss epistemic uncertainties in particular until a consensus was reached. The parameters used for evaluation, i.e., the earthquake location and geometry, magnitude, and probability of occurrence, are interrelated and it may not always be possible to rigorously separate them. We came up with various ideas, such as using a matrix to clearly identify points for discussion, to foster a common goal and understanding among experts, and to successfully complete the project. We carried out in-depth discussions on the different seismic sources around the Ikata site to ensure that we captured the CBR of TDI in line with the requirements of the SSHAC Level 3 Guidelines and were able to develop highly reliable SSC models that are specific to the individual site. This paper presented a general description of the SSC models developed using the SSHAC Level 3 Guidelines as well as provided discussions on differences with the model developed by the HERP and on branch parameters with large impacts on seismic hazard. In this way, we provided a substantive demonstration of the effectiveness of the process in the SSHAC Level 3 Guidelines, as well as an assessment of the range of uncertainty and degree of impact in order to show the key points to focus on in future surveys and studies from the perspective of impact on assessment of seismic hazard. Finally, we believe that the various findings obtained here could be expanded and developed into other areas in the seismology and earthquake engineering fields, and could serve as a significant step toward the development of future PSHAs with a focus on accurately and objectively evaluating uncertainties.

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