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DEVELOPMENT OF GROUND MOTION CHARACTERIZATION MODEL AT THE IKATA SITE BASED ON GUIDELINES FOR SSHAC LEVEL 3

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ABSTRACT: In overseas countries, probabilistic risk assessment of nuclear power plant is based on probabilistic seismic hazard analysis (PSHA) applying the SSHAC (Senior Seismic Hazard Analysis Committee) Level 3. The Ikata SSHAC project is the first attempt in Japan to apply the SSHAC Level 3 seismic hazard analysis to a nuclear power plant, the Ikata Power Plant Unit 3. The characteristics of the Ikata site is that the Median Tectonic Line fault zone is located near the site and the hard rock site. Therefore, in order to take into account the epistemic uncertainty of the seismic motion, we introduced both ground motion prediction equation (GMPE) and fault rupture model simulation for evaluating ground motions, and analyzed the variations in ground motion near the seismic source. The results of this study are significant from the viewpoint of accurate and objective evaluation of uncertainty, and should be extended to subsequent PSHA.

Keywords: *Probabilistic seismic hazard analysis, SSHAC Level 3, Epistemic uncertainty, Ground motion prediction equation (GMPE), Fault rupture model, Variations in ground motion near the seismic source*

1. INTRODUCTION

The evaluation of ground motion for the seismic safety of nuclear power plants and similar facilities is broadly divided into two types: scenario-based ground motion evaluation, an example of which is the "Strong Motion Evaluation Assuming an Earthquake in the Yamasaki Fault Zone"[1], and probabilistic ground motion evaluation, an example of which is the "National Seismic Hazard Maps of Japan"[2], from evaluations by the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion (hereinafter Earthquake Headquarters). The approaches of the two types to uncertainties involved in ground motion prediction are fundamentally different. In scenario-based ground motion evaluation, ground motion is predicted by referring to past seismic records and active fault distributions to draw safety margins by using the engineering judgment of experts based on the latest findings and experience. On the other hand, in probabilistic ground motion evaluation, various uncertainties are quantitatively evaluated using probabilistic methods in order to systematically include factors of uncertainty and ensure comprehensiveness and logic. This paper discusses the uncertainties of ground motion characterization used in probabilistic seismic hazard analysis (PSHA), which calculates the probability distribution of ground motion metrics such as maximum acceleration amplitude and response spectrum.

The uncertainties considered in PSHA are epistemic uncertainty and aleatory variability (Fujiwara et al.[3]). Epistemic uncertainty is the uncertainty that arises from differing interpretations and opinions among experts due to lack of experience or data on earthquake occurrence or ground motions, which cannot be addressed by statistical data. Aleatory variability refers to the uncertainty caused by the heterogeneity of natural phenomena, which can be expressed by modeling the probability distribution based on collected observational data. In PSHA, epistemic uncertainty is expressed by logic trees with branches set up for each parameter on which experts disagree. To obtain PSHA results that can gain the public's trust, it is essential to have a framework for discussion that enhances accountability, quality, and transparency with respect to epistemic uncertainties, which may be significantly influenced by the subjective views of the evaluator.

In the second half of the 1980s, two institutes in the United States independently carried out PSHA studies for the same seismic source and site and obtained results showing a large difference in their mean hazard curves. To study the cause of this difference, a committee called the Senior Seismic Hazard Analysis Committee (SSHAC) was established (Sakai[4]). The results of their study were summarized in the SSHAC report[5], which acknowledged that the cause of the difference was not in the technical aspect but in the procedures used to reflect the opinions of experts, in other words, the cause was the procedures used to consider epistemic uncertainties. Consequently, the SSHAC report defined the necessary study processes for PSHA and established guidelines for conducting PSHA that set study levels according to the degree of importance and uncertainties of the project. The SSHAC Guidelines set four levels based on the degree of importance and level of uncertainties of the facility in question. In order to obtain objective and suitable assessments, the guidelines clearly defined the steps for studies, significant issues, and the roles of relevant parties for each level. The difference in implementation between the four levels of SSHAC is as follows. At Level 1, the Technical Integrator (TI), composed of expert/s who perform the evaluation, constructs the models themselves based on published data. For Level 2, the models are constructed with the participation of relevant parties in addition to the TI. In contrast, Level 3 requires the TI team to meet and conduct technical studies together and hold at least three open workshops to debate with outside experts; so, there is a significant difference between Levels 2 and 3[4]. At Level 4, each member of the TI team is required to propose their own models, although Level 3 is considered to be sufficient in terms of the quality of the results[4]. Hence, for the most part, SSHAC Level 3 has been applied to projects involving nuclear power plants and similar facilities outside Japan and the updated guidelines[6), 7] that take into account the experience from these implementations have become the latest operational standards. Kameda[8] referred to these guidelines as the SSHAC Level 3 Guidelines, which we adopted in this paper.

In Japan, the concept of residual risk was introduced in the September 2006 revision of the Regulatory Guide for Reviewing Seismic Design[9], and the Implementation Standards for Probabilistic Risk Assessment was published by the Atomic Energy Society of Japan[10], although these approaches did not necessarily lead to risk quantification or other actual application. However, the recent 2011 accident at the Fukushima Daiichi Nuclear Power Station of the then Tokyo Electric Power Company was a turning point, requiring further safety improvements from nuclear power plants and making it necessary to reduce the risks associated with low-frequency external events such as earthquakes and tsunamis. The key issues that emerged were on establishing probabilistic risk assessments and risk-informed decision-making based on these assessments (for example, Takada[11]). Under these circumstances, Shikoku Electric Power Company and the Nuclear Risk Research Center of the Central Research Institute of Electric Power Industry implemented the Ikata SSHAC Project to conduct the first PSHA using SSHAC Level 3 in Japan as a voluntary initiative to improve the safety of the Ikata Power Station Unit 3 (Ikata site) located in northwestern Shikoku (Onishi et al.[12]).

Looking back on our experience implementing PSHA based on the SSHAC Level 3 Guidelines in Japan, where the seismo tectonics and databases as well as the industries of experts participating in the project differ from those in the United States, identifying the significant issues and challenges for the application of the guidelines are extremely important to advancing PSHA in Japan. From the Ikata SSHAC Project Final Report[13] compiled as a result of the Ikata SSHAC Project, this paper focuses on the evaluation of ground motion characterization, summarizes and presents the discussions on epistemic uncertainties——the core of logic tree model construction—as well as the technical issues that emerged as a result of the discussions. Note that the evaluation of seismic source characterization of the Ikata SSHAC Project is shown in Kumamoto et al.[14].

2. SIGNIFICANCE OF THE IKATA SSHAC PROJECT

The most important concept of the SSHAC Guidelines is developing models for evaluating epistemic uncertainty based on the "Center, Body, and Range of Technically Defensible Interpretations" (CBR of TDI) (Fig. 1). Note that in this paper, the "Center" referred to in the SSHAC Guidelines is the "central point/value" of expert opinions and does not correspond to the statistical term "median."

The process of our study using the SSHAC Level 3 Guidelines are as follows. In the first stage called "Evaluation", we asked Resource Experts (REs) to provide relevant data in an objective manner. In the first workshop, the REs explained the available data and methods for hazard significant issues of the PSHA. In the second workshop, we asked Proponent Expert (PEs) to advocate for their specific model or method and to directly discuss and debate the validity, reliability and other particulars of the model or method with the TI team and other PEs. In the second stage called "Integration", we first created preliminary models based on the results of the discussions above and then performed preliminary hazard calculations using the models. The Participatory Peer Review Panel (PPRP) reviewed the calculation results (especially the sensitivity analysis results) and the developed models to ensure sure that the TI team's study was technically valid in terms of CBR of TDI and that the process conformed to the SSHAC Guidelines. In the third workshop, we received comments and feedback from the PPRP on the preliminary models, after which we moved on to preparing the final models. The final stage called "Documentation" required that the entire process of the study, including the basis of the final models and the PSHA results, be properly documented and published in the final report.

The greatest value of the SSHAC Level 3 Guidelines lies in its ability to ensure accountability through the CBR concept, quality through the TDI, and transparency through open workshops and the publication of the final report, based on a careful implementation process, and to serve as a framework for deliberations to produce widely acceptable models from both academic and technical perspectives. The Ikata SSHAC Project respected this framework to the fullest extent possible in carrying out its study in accordance with the SSHAC Level 3 Guidelines[8)]. To compensate for the lack of experience of SSHAC Level 3 projects in Japan, we invited overseas experts with extensive experience as advisors and received training and advice on the significance and procedures of the SSHAC Level 3 Guidelines to help deepen our understanding. Additionally, because of the time and work limitations of industry-based experts participating in the Ikata SSHAC Project compared to similar projects in the United States and other countries, we set up a support team to prepare and provide basic documents for discussions and looked for other ways to conduct deliberations that aligned with the situation in Japan. Although the circumstances differ, the TI team was still responsible for the technical study and the compiled results in accordance with the SSHAC Guidelines. Furthermore, because there are various seismic sources around the Ikata site requiring a wide range of discussions, we regularly held informal preparatory meetings between formal meetings stipulated in the SSHAC Level 3 Guidelines to strengthen the deliberations.

Following the SSHAC Level 3 Guidelines, the TI team of the Ikata SSHAC Project is composed of the seismic source characterization (SSC) TI team, consisting of seven experts to develop seismic source characterization models, and the ground motion characterization (GMC) TI team, consisting of seven experts to construct ground motion characterization models, with the Project Technical Integrator overseeing the overall direction of discussions by both teams and the five-member PPRP reviewing the discussions. In the first and second workshops, a total of 52 outside experts (REs and PEs) were invited for discussions with the TI team. Following these workshops, the TI team began the work of developing the models and discussed them with the PPRP in the third workshop, the results of which led to stable logic tree models that provide accountability, quality, and transparency. The Ikata SSHAC Project started in the spring of 2016 and concluded with the PPRP Closure Letter in the fall of 2020. The project's entire process and basis were published in a final report[13)] on the Shikoku Electric Power website.

Enhancing the accountability, quality, and transparency of risk assessments based on PSHA is extremely important 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. 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 nuclear power plant operator that carried great significance in its attempt to refine the scientific and technical evaluation methodologies of PSHA at a level beyond the current state of regulations[8)].

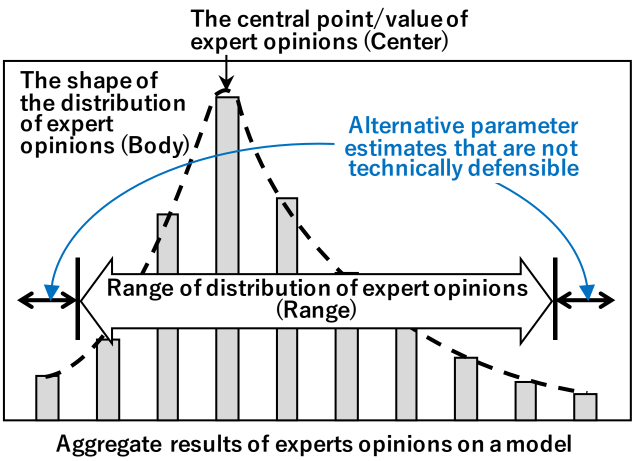


Fig. 1 Conceptual diagram of the center, body, and range of technically defensible interpretations (CBR of TDI)

3. OVERVIEW OF GMC MODEL DEVELOPMENT

For the seismo tectonics at the Ikata site in northwest Shikoku, the site is located at the northern limit of the assumed focal region of the Nankai Trough Megathrust Earthquakes, with observed seismic activity from blind sources in the Philippine Sea Plate subducting deep in the northwestern direction at the deep zone. Aside from the Median Tectonic Line Active Fault Zone (MTLAFZ), which is a long active fault with a right-lateral strike-slip running east-northeast to west-southwest, several right-lateral strike-slip active faults running parallel to the fault zone are distributed close to the site. Hence, earthquakes caused by these active intraplate faults may occur at the seismogenic layer of the landward plate where the site is located, as well as blind earthquakes in landward plates where active faults have not been identified yet (Fig. 2). Therefore, six types of earthquakes were used for seismic source characterization: the Nankai Trough Megathrust Earthquakes, blind earthquakes in the Philippine Sea Plate, MTLAFZ earthquakes, other active intraplate fault earthquakes, blind earthquakes in landward plates, and earthquakes smaller than the characteristic scale of active intraplate faults[13].

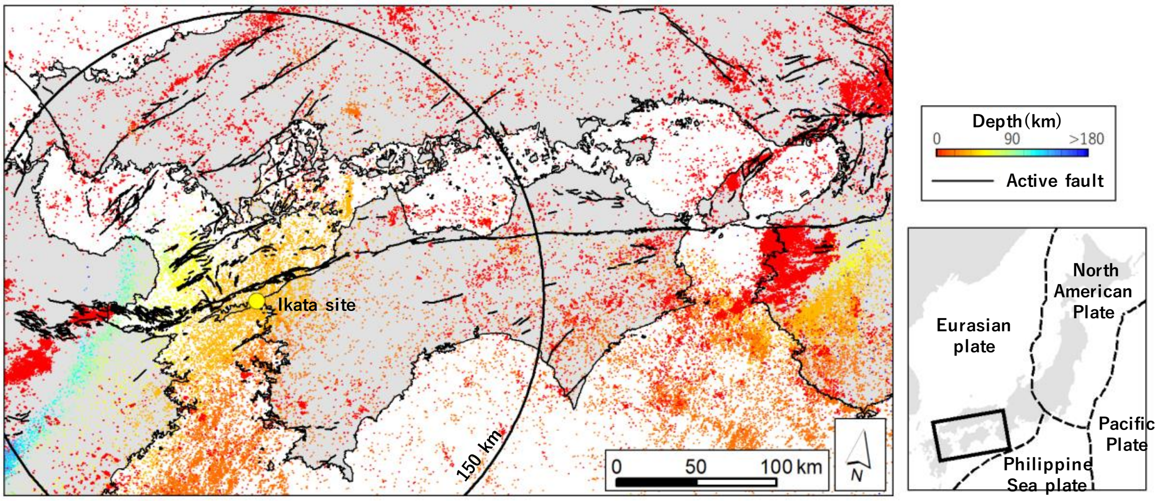


Fig. 2 Seismic activity and active fault distribution around the Ikata site (Seismic source distribution is from October 1997 to May 2016, M 1 or more.)

For the ground conditions at the site, the Sadamisaki Peninsula where the site is located is characterized by a wide distribution of basic schist belonging to the Sambagawa metamorphic zone. PS logging at the site showed that Vs = 2 km/s is exceeded at fresh layers near the surface, and gradually increased at greater depth, reaching over Vs = 3 km/s approximately 2 km underground. The ground at the point for seismic hazard evaluation was hard with Vs = 2.6 km/s, and almost corresponds to seismic bedrock. Detailed subsurface exploration did not reveal any irregular structures that could cause ground motion amplification. Moreover, seismic observation records since 1975 did not find any unusual ground amplification. Thus, the subsurface structure of the Ikata site was assessed to be horizontally stratified and homogeneous for the purpose of ground motion evaluation. Based on the above, we judged that it was not necessary to consider amplifications by the subsurface structure at depths shallower than the seismic bedrock at 2 km depth and that ground motions on the surface may be calculated directly without using subsurface structure models at the Ikata site[13].

Based on the SSHAC Level 3 Guidelines, the GMC TI team is responsible for constructing logic tree models to evaluate ground motion characteristics at each seismic source, to correspond to the logic tree models of seismic source characteristics constructed by the SSC TI team. Figure 3 shows a general outline of the GMC logic tree models (GMC models) developed in the Ikata SSHAC Project. To develop the GMC models, taking into account the fact that the Ikata site is situated on hard rock located close to the Median Tectonic Line Active Fault Zone, we constructed logic trees to evaluate epistemic uncertainty. Among the key considerations for the GMC models were given by the following three points.

The first point (point (1) in Fig. 3) was the use of multiple ground motion prediction equations (GMPEs) that have been in use both in and out of Japan to account for the epistemic uncertainty in GMPEs, from the perspective of considering the uncertainty in the center of expert opinions on the use of ground motion evaluations based on GMPEs that are widely used by Earthquake Headquarters and others for PSHA (GMPE and branching with seven equations in Fig. 3). We then performed corrections using site observation records on the GMPEs used here, in order to consider the ground conditions at the Ikata site in the evaluation.

The second point (point (2) in Fig. 3) was the full adoption of an evaluation based on ground motion simulation methods using fault rupture models with high applicability to areas near the seismic source, as the Median Tectonic Line Active Fault Zone is located close to the Ikata site. Using the ground motion simulation methods in addition to GMPE, we account for epistemic uncertainty in the methodology of ground motion evaluation. Moreover, branches were set to consider the uncertainty in evaluation results using fault rupture models and account for the epistemic uncertainty in the ground motion simulation method (simulation (fault rupture model) and branching with three branches to account for uncertainty in the central value (Fig. 3)).

The third point (point (3) in Fig. 3) was the setting of the logic tree to consider epistemic uncertainty related to aleatory variability in ground motion evaluation results. Using the analysis results from ground motion simulation, we studied the correction for variations in ground motion at evaluation points located near the seismic source. We then incorporated the standard variation assumed at the individual site (Ikata single station σ branch in Fig. 3) and the correction specific to evaluation points located near the seismic source (correction σ by simulation branch in Fig. 3) into the model. We also studied the probability distribution of the variation considering that ground motion is a finite physical phenomenon, and constructed models reflecting the results (branches for lognormal and lognormal (truncation) distributions in Fig. 3).

Furthermore, although GMC models differ in details depending on the characteristics of each seismic source, we generally constructed models as shown in Fig. 3 for each seismic source[13]. In the following section, we will discuss the details of the study, focusing on the three points given above.

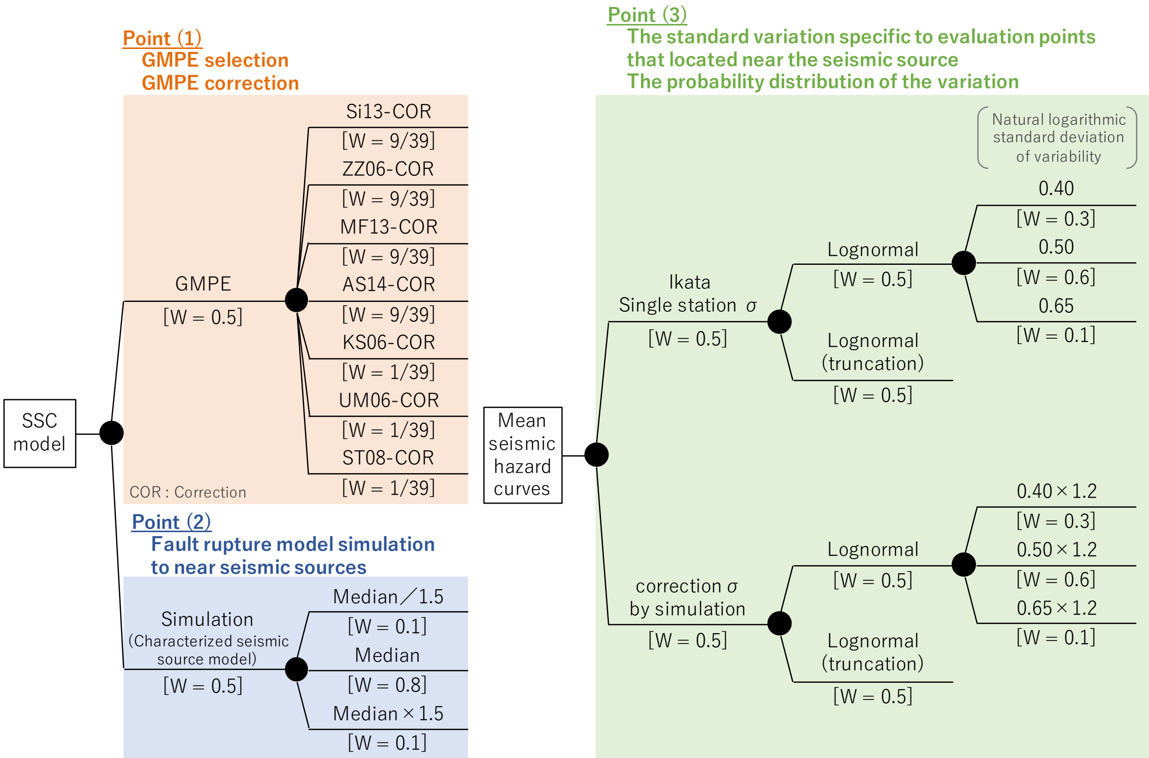


Fig. 3 General outline of GMC logic tree models (W indicates the weight of each branch in the figure)

4. KEY CONSIDERATIONS FOR THE GMC MODELS

4.1 Evaluation based on GMPE (Point (1))

4.1.1 Selecting GMPEs for the study

Since ground motion evaluation based on GMPE is an empirical method that uses a large number of observation records from the past, ground motion levels may be accurately evaluated with a few input parameters as long as the ground motion is within the range of the dataset of observation records used in developing the equation (earthquake magnitude, fault distance, ground conditions, etc.). However, if the GMPE is used beyond the scope of its dataset, the evaluation will be based on extrapolation; hence, it is important to thoroughly validate its applicability by considering ground conditions at the site, seismo tectonics, and other features of the site.

Some of the characteristics that have to be taken into account when selecting GMPEs that can be applied to the Ikata site are as follows: for ground conditions, that the ground at the Ikata site is made of extremely hard bedrock at Vs = 2.6 km/s; for seismo tectonics, that the long Median Tectonic Line Active Fault Zone is in close proximity about 8 km away and that there is a possibility of a megathrust earthquake at the Nankai Trough in the maximum M 9-class. In light of these characteristics, we selected GMPEs for the Ikata SSHAC Project that meet the following requirements: can evaluate over a wide band of periods from 0.02 s (or maximum acceleration: PGA) to 5.0 s, can evaluate by type of earthquake (intraplate crustal earthquake, interplate earthquake, oceanic intraplate earthquake), and can be applied to near-field earthquakes. During the selection, we took into account the GMPE's historical application and performance in Japan. Moreover, for GMPEs published after 1964 in Douglas[15], we referred to Douglas[15] since it provides an overview of the database used for construction, the covered period, the types of earthquakes, shapes of the equation, etc. that are comprehensively organized, compared, and updated every year. Note that in this study, we referred to data through 2018.

We selected 16 GMPEs that may be considered applicable to the Ikata site (each equation is referred

Table 1 List of selected GMPEs for the Ikata SSHAC Project

GMPE	Symbol	Database	Range of Magnitude (C:Crustal earthquakes, S：Subduction earthquakes)	Distance	Ground condition	Ref.
Noda et al.(2002)	N02	Japan	C：5.5～7.3（Mj），S：5.5～7.0（Mj）	28～202 km	500≦Vs≦2700 m/s	16)
Kanno et al.(2006)	KN06	Mainly Japan	C・S：5.5～8.2	1～500 km	100≦Vs30≦1400 m/s	17)
Zhao et al.(2006)	ZZ06	Mainly Japan	C：5.1～6.8, S：5.0～8.3	0.3～300 km	Hard rock (Vs=2000 m/s)	18)
Uchiyama and Midorikawa(2006)	UM06	Mainly Japan	C：5.5～6.9, S：5.5～8.3	Within 300 km	150≦Vs30≦750 m/s	19)
Kataoka et al.(2006)	KS06	Japan	C：4.9～6.9, S：5.2～8.2	Within 250 km	Engineering bedrock (about Vs=700 m/s)	20)
Sato(2008)	ST08	Japan	C：4.9～6.9	Within 200 km	Engineering bedrock (Vs=600～800 m/s)	21)
Sato(2010)	ST10	Japan	S：6.0～8.2(Pacific Ocean), 5.5～7.4(Philippine Sea)	Within 250 km	400≦Vs≦3000 m/s	22)
Si et al.(2013)	Si13	Japan	C：5.6～6.9, S：5.6～9.1	0～300 km	Hard rock (Vs≧2000 m/s)	23)
Morikawa and Fujiwara (2013)	MF13	Mainly Japan	C・S：5.5～9.0	Within 200 km	100≦Vs30≦2000 m/s	24)
Sasaki and Ito(2016)	SA16	Japan	C：4.7～7.0, S：4.9～9.0	Within about 200 km	Dam rock foundation (Vs=700～1500 m/s)	25)
Abrahamson et al. (2014)	AS14	Mainly overseas	C：3.0～8.5	0～300 km	100≦Vs30≦2000 m/s	26)
Abrahamson et al. (2016)	AG16	Mainly overseas	S：6.0～8.4(Interplate), 5.0～7.9(Intraplate	Within 300 km	90≦Vs30≦2000 m/s	27)
Boore et al.(2014)	BSSA14	Mainly overseas	C：3.0～8.0(Stlike-slip fault , Reverse fault) 3.0～7.0(Normal fault)	0～400 km	150≦Vs30≦1500 m/s	28)
Campbell and Bozorgnia (2014)	CB14	Mainly overseas	C：～8.5(Stlike-slip fault), ～8.0(Reverse fault) ～4.5(Normal fault)	0～300 km	150≦Vs30≦1500 m/s	29)
Chiou and Youngs (2014)	CY14	Mainly overseas	C：3.5～8.5(Stlike-slip fault) 3.5～8.0(Normal fault , Reverse fault)	0～300 km	180≦Vs30≦1500 m/s	30)
Idriss(2014)	I14	Mainly overseas	C：5.0～7.9	0.2～150 km	450≦Vs30≦2000 m/s	31)

*GMPEs in colored rows used corrected GMPE equations as described later.

to hereinafter using the code names shown in Table 1). Note that it is important to use GMPEs that are applicable to the ground conditions at the site in order to improve the accuracy of ground motion evaluations using GMPE. However, since we would perform corrections later to consider ground conditions at the Ikata site, we did not include ground conditions in the selection criteria at this stage of the Ikata SSHAC Project. Moreover, vertical motion considerations are also an essential part of the deliberations in the seismic design of nuclear power plants. However, some of the selected GMPEs did not include an equation for vertical motion. Hence, for GMPEs that include equations for vertical motion, we first corrected the proposed equations based on ground conditions at the Ikata site and used them to evaluate the vertical motion. For GMPEs that did not include equations for vertical motion, the response spectral ratio (vertical/horizontal ratio) was calculated using observation records at the Ikata site and KiK-net, after which the vertical motions were evaluated by multiplying the equations for horizontal motion by the calculated ratio[13)].

Using the selected GMPEs, we compared their ground motion levels using a fixed earthquake magnitude, fault distance, and focal depth. Ground conditions were set to Vs = 2.6 km/s or the upper limit of ground conditions for each GMPE. Figure 4 shows a comparison of GMPEs for intraplate crustal earthquakes. Also, if the fault distance is used for the distance between the seismic source and the site, the mean intensity of maximum ground motions (maximum acceleration and maximum velocity) from the 2011 off-the-Pacific-coast-of-Tohoku Earthquake is roughly the same as that from the Mw 8.3 Tokachi-oki Earthquake. Therefore, when considering the applicability to M 9-class large earthquakes for interplate earthquakes, it should be noted that there is a saturation effect on the strength of ground motions with respect to the earthquake magnitude (for example, Tsukasa et al.[32)]). Figure 5 shows a comparison of GMPEs for interplate earthquakes, with magnitudes at Mw 8.3 and Mw 9.0.

The figures show that there are differences in predictions from each GMPE, which may be attributed to the fact that the ground motion databases and range of applications for ground conditions are different for each GMPE (Figs. 4 and 5(a)). Comparing by magnitude for each GMPE for interplate earthquakes (Fig. 5(b)), the figures show that the ground motion levels for Si13[23)] and MF13[24)], which include the 2011 off-the-Pacific-coast-of-Tohoku Earthquake in their datasets, are almost the same at magnitudes of Mw 8.3 and Mw 9.0. These are GMPEs that take into account the fact that although the range of sites with large ground motion levels expand with the magnitude of the earthquake, there is a peaking effect for ground motion levels at individual sites. On the other hand, many of the other GMPEs have larger ground motion levels at Mw 9.0. In particular, since these are several times larger for KN06[17)], UM06[19)], and KS06[20)] than for the other GMPEs, there is a possibility of overestimation. Note that each GMPE shown in Table 1 differs in the definition of horizontal direction (for example, the geometric mean of the two horizontal components or the maximum value), and the differences in definition of horizontal direction have not been corrected in the comparisons given in Figs. 4 and 5. Therefore, the differences in predicted values include the effect of differences in the definition of horizontal direction, although this effect is considered to be small compared to the differences caused by the factors mentioned above.

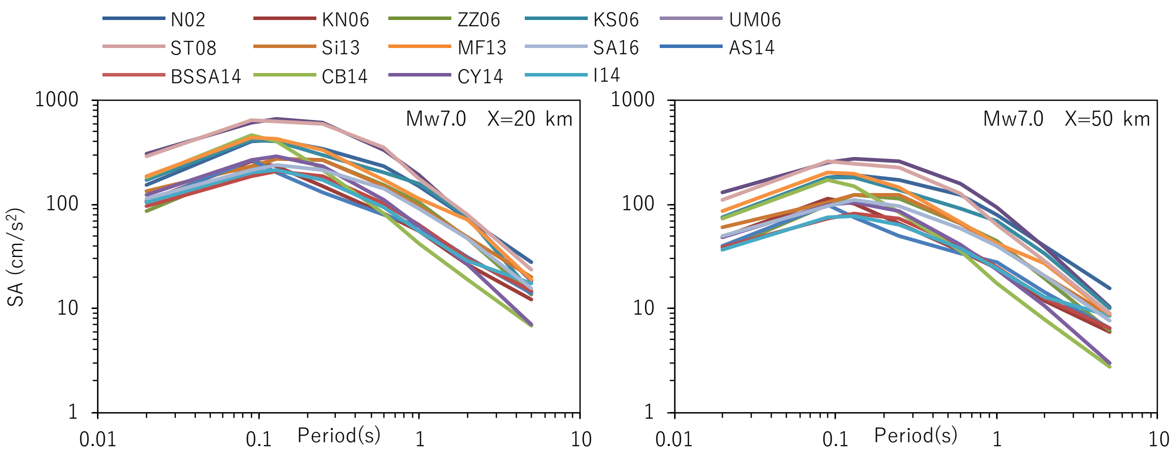
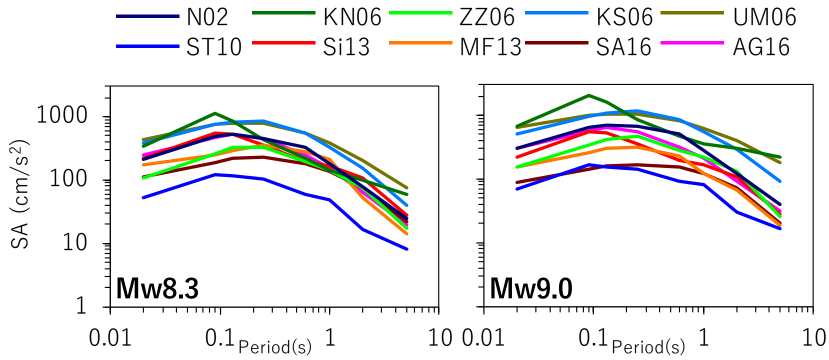
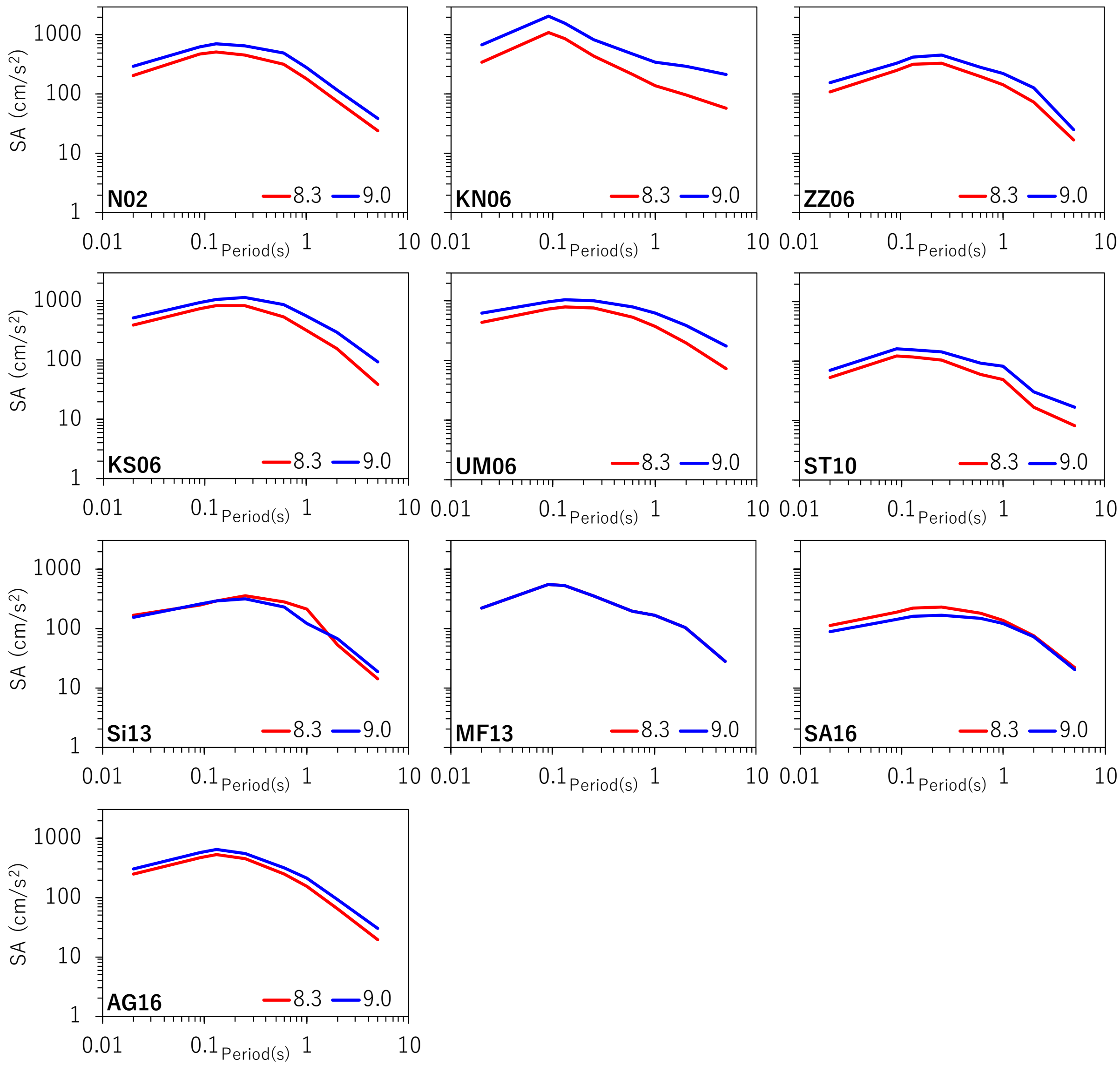


Fig. 4 Comparison of predictions by GMPE for intraplate crustal earthquakes (focal depth: 10 km)



(a) Comparison of predictions by GMPE for each earthquake magnitude



(b) Comparison of predictions by magnitude for each GMPE

Fig. 5 Comparison of predictions by GMPE (interplate earthquakes/fault distance: 50 km/focal depth: 20 km/horizontal direction)

4.1.2 GMPE correction considering the ground conditions at Ikata site

The level of seismic motions observed from an earthquake is affected by the earthquake source characteristics and the propagation characteristics associated with the positional relationship between the observation site and the source, and greatly depends on the ground conditions at the observation site. Using an equation that can appropriately evaluate the ground motion characteristics at the Ikata site is ideal when evaluating ground motions based on GMPE. However, considering that the ground at the Ikata site is extremely hard bedrock with homogeneous ground conditions that do not amplify seismic motion, most of the selected GMPEs are outside of their applicable range.

In order to apply the selected GMPEs to the Ikata site, we corrected the ground amplification characteristics based on Morikawa et al.[33), 34)] In this method used in the study, the shaking characteristic to each earthquake (source characteristics) is defined as the event coefficient S_i, the shaking characteristic to each site (propagation characteristics and ground amplification characteristics) is defined as the site coefficient G_j. The following Eqs. (1) and (2) were iteratively calculated until the site coefficient G_j converges sufficiently. The GMPE predictions were corrected using the final event coefficient S_i and site coefficient G_j obtained. The calculated site coefficient was determined on the condition that the site coefficients at all the stations used for correction averages to approximately zero, and were obtained relative to the average ground conditions at all the stations.

$$S_i(T_k) = \left(\frac{1}{M}\right) \sum_{j'=1}^{M} \left[\ln \left\{ \frac{O_{ij'}(T_k)}{P_{ij'}(T_k)} \right\} - G_{j'}(T_k) \right] \tag{1}$$

$$G_j(T_k) = \left(\frac{1}{N}\right) \sum_{i'=1}^{N} \left[\ln \left\{ \frac{O_{i'j}(T_k)}{P_{i'j}(T_k)} \right\} - S_{i'}(T_k) \right] \tag{2}$$

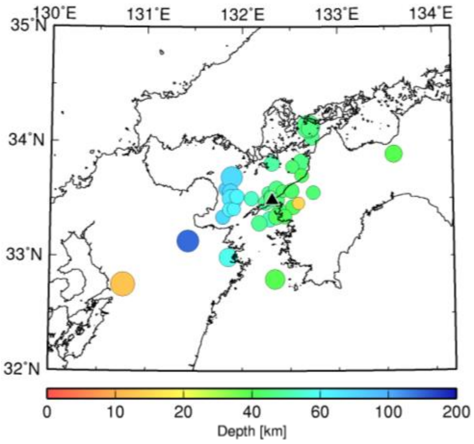
where

$S_i(T_k)$	: event coefficient of earthquake i	$G_j(T_k)$	: site coefficient of station j
O_{ij}	: observed value of earthquake i from station j	P_{ij}	: predicted value of earthquake i from station j
M	: number of records of earthquake i (number of stations)	N	: number of records from station j (number of earthquakes)
T_k	: kth period		

Of the GMPEs shown in Table 1, the N02[16)] equation, which is considered as difficult to apply to near-field earthquakes, and the SA16[25)] equation, which is based on records on dam bedrock, were not included in the correction. The GMPEs to be corrected were represented by MF13[24)] equation, because the database of KN06[17)] equation is included in MF13[24)] equation. The NGA-West2 GMPEs (AS14[26)], BSSA14[28)], CB14[29)], CY14[30)], and I14[31)]), which used the same database to develop their equations, were represented by the AS14[26)] equation. The data used for the study were observation records from the Ikata site (G.L. −5 m), from K-NET and KiK-net by the National Research Institute for Earth Science and Disaster Resilience (underground and surface), from the Japan Meteorological Agency (JMA) seismometers, and from strong motion observation at port areas by the Port and Airport Research Institute. Thirty-eight earthquakes observed at the Ikata site with acceleration greater than 2 cm/s^2 were used (Fig. 6), with the 5%-damped response spectral acceleration (RotD50[35)]) as the measure of ground motion intensity.

Here, the event coefficient of intraplate crustal earthquakes and interplate earthquakes cannot be calculated because all the earthquakes that occurred around the site were oceanic intraplate earthquakes except for two (Nos. 36 and 37 in Fig. 6). On the other hand, the site coefficient is obtained by subtracting the event coefficient and is considered to be independent of the type of earthquake. In the Ikata SSHAC project, we used all 38 earthquakes for each equation of intraplate crustal earthquakes and trench earthquakes to calculate one site coefficient. Based on the above, we decided on a policy for the PSHA of using GMPEs corrected with only the site coefficient.

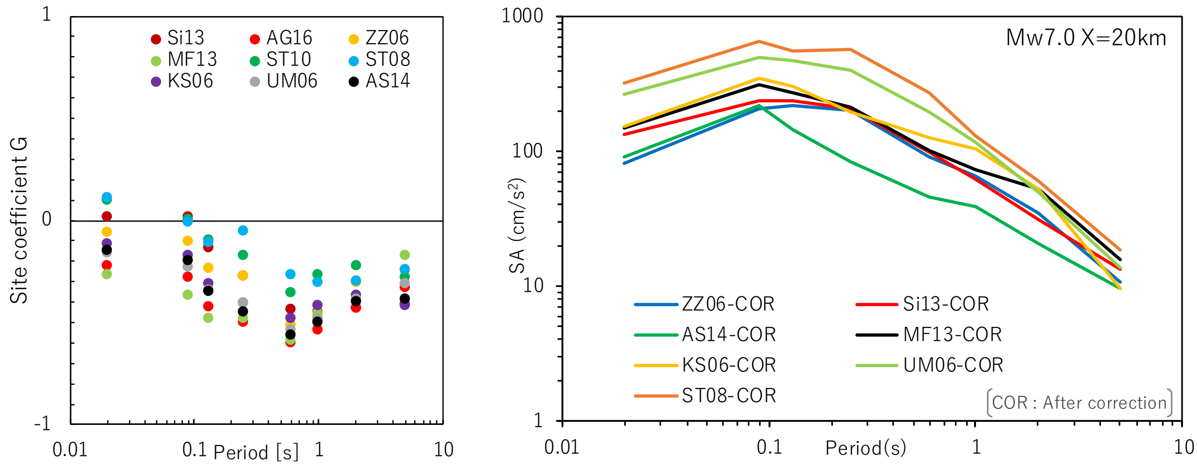
Figure 7 shows a comparison of site coefficients obtained based on the above conditions and ground motion levels from corrected GMPEs (intraplate crustal earthquakes). The figure shows that the site coefficients (natural logarithm) are generally less than zero, in other words, the values are generally smaller than the predicted values of the GMPEs before correction, reflecting the tendency of ground amplification to be small at the Ikata site. Moreover, differences of several times or more in ground motion levels predicted by the GMPEs remain even after correction. In particular, UM06[19], KS06[20], and ST08[21] equations have smaller upper limits of the applicable range of S-wave velocity of the ground than that of the ground at the Ikata site, and show larger ground motion levels. This may be due to the fact that there are no stations around the Ikata site with the same ground conditions as the Ikata site. In other words, the residuals between the predicted values at bedrock point with Vs = 2.6 km/s and the observed values at each station on soft ground conditions should have been evaluated as site coefficients, but were instead evaluated as having event coefficients that are large (source characteristics are large).



No	Date	Epicenter	Mj	Dep.	No	Date	Epicenter	Mj	Dep.
1	2000/9/7	Bungo Channel	4.3	45	20	2006/11/19	Bungo Channel	4.2	41
2	2001/1/5	Aki-nada	4.0	47	21	2007/4/26	Touyo	5.3	39
3	2001/1/9	Iyo-nada	4.6	50	22	2009/1/25	Iyo-nada	4.4	78
4	2001/3/24	Geiyo EQ	6.7	51	23	2009/3/28	Iyo-nada	3.9	83
5	2001/3/25	Aki-nada	4.4	51	24	2010/4/17	Nanyo	4.3	43
6	2001/3/26	Aki-nada	5.0	49	25	2011/6/29	Iyo-nada	3.8	64
7	2001/4/25	Hyuga-nada	5.6	42	26	2012/5/25	Iyo-nada	4.0	63
8	2002/3/25	Aki-nada	4.7	46	27	2012/9/8	Iyo-nada	4.5	50
9	2002/4/6	Southwestern Ehime	4.5	42	28	2012/12/22	Iyo-nada	4.5	47
10	2002/10/13	Bungo Channel	4.7	43	29	2014/3/14	Iyo-nada	6.2	78
11	2003/5/31	Iyo-nada	4.5	65	30	2014/10/16	Iyo-nada	4.0	41
12	2004/4/20	Iyo-nada	4.6	48	31	2015/2/3	Nanyo	3.9	44
13	2005/5/25	Bungo Channel	4.6	54	32	2015/7/3	Iyo-nada	3.9	43
14	2005/9/4	Iyo-nada	4.3	54	33	2015/7/13	Southern Oita	5.7	58
15	2006/2/1	Iyo-nada	4.3	46	34	2015/7/24	Nanyo	4.6	44
16	2006/5/28	Iyo-nada	4.3	80	35	2015/8/21	Bungo Channel	4.3	48
17	2006/6/6	Iyo-nada	3.6	49	36	2016/2/12	Nanyo	3.8	15
18	2006/6/12	Western Oita	6.2	146	37	2016/4/16	Kumamoto EQ	7.3	12
19	2006/9/26	Iyo-nada	5.3	70	38	2016/8/15	Iyo-nada	4.3	71

Earthquake specifications are from the Japan Meteorological Agency (Dep.(depth) in kilometers)

Fig. 6 Earthquake data used for site correction



(a) Site coefficient (b) Ground motion level from GMPEs after correction

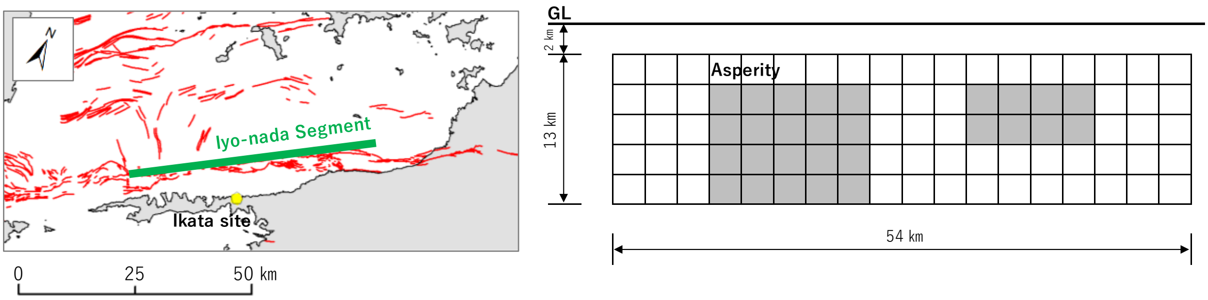
Fig. 7 Comparison of site coefficients and ground motion levels from GMPEs after correction (intraplate crustal earthquakes) (horizontal direction)

Based on the above considerations, the GMC TI team constructed the logic tree shown in point (1) in Fig. 3. The issue remains with regard to site correction for GMPEs with smaller upper limits of the applicable range of S-wave velocity of the ground than that of the Ikata site; hence, it is normally considered appropriate to judge these GMPEs as basically inapplicable. However, since GMPEs in Japan were created using their own unique databases, we can consider their predictions to include discrete uncertainties; so, we decided to take the uncertainty in the central value into account in PSHA by using multiple GMPEs. Therefore, we assigned weights to the branches of the logic tree according to the applicable range of S-wave velocity of the GMPE (value of W in Fig. 3). Specifically, branches for GMPEs that are applicable up to Vs = 2.0 km/s (ZZ06[18], ST10[22], Si13[23], MF13[24], AS14[26] and AG16[27]) are express the ground motion levels that may realistically be expected at the Ikata site (center) and branches for the other GMPEs (UM06[19], KS06[20], and ST08[21]) are account for the epistemic uncertainty in GMPEs (equivalent to the upper end of the range of expert opinions). And we set the weight of the former GMPEs to be 9 times the weight of the latter.

4.2 Evaluations based on ground motion simulation using fault models (Point (2))

The PSHA that have been implemented both in Japan and other countries was commonly performed using GMPEs because of the simplicity of evaluation and because evaluations focusing on individual sites located near seismic sources were few in number. On the other hand, there are also issues with the use of GMPEs, including the insufficient number of observation records of large-scale earthquakes with sources located near sites, such as in the case of MTLAFZ earthquakes.

Hence for the Ikata SSHAC Project, we set up a branch for evaluations based on ground motion simulation using fault models that are applicable to ground motion evaluations of near-field earthquakes, in order to address MTLAFZ earthquakes where the source is located near the site (point (2) in Fig. 3). In Japan, ground motion evaluation methods using characterized seismic source models found to be consistent with many seismic observation records in the past, and have been widely adopted as a strong motion prediction method[36]. In other countries, the ground motion simulation methods in use include GP by Graves and Pitarka[37], SDSU by Mai et al.[38], UCSB by Schmedes et al.[39], CSM by Zeng et al.[40], EXSIM by Motazedian and Atkinson[41] and Song[42], which have been validated for their ability to describe observation records under the same conditions and metrics by the Southern California Earthquake Center Broadband Platform (SCEC BBP[43), 44)]). Consequently, we compared ground motion evaluations using the characterized seismic source models and the SCEC BBP fault models for earthquakes at the Iyo-nada Segment of the Median Tectonic Line Active Fault Zone, which is the closest to the Ikata site. For the specifications of the Iyo-nada Segment, we referred to the segmentation carried out by the SSC TI team in accordance with the concept of seismic, geometric, and behavioral segments[13], and used a length of 54 km, a vertical dip, and a source fault with depths of 2 km for the top and 15 km for the bottom. Figure 8 shows the planar position and fault rupture model of the Iyo-nada Segment.



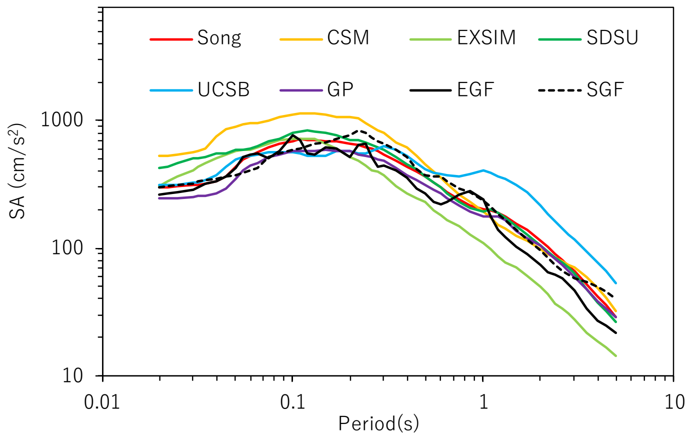
(a) Planar position (b) Fault rupture model example

Fig. 8 Planar position and fault rupture model of the Iyo-nada Segment

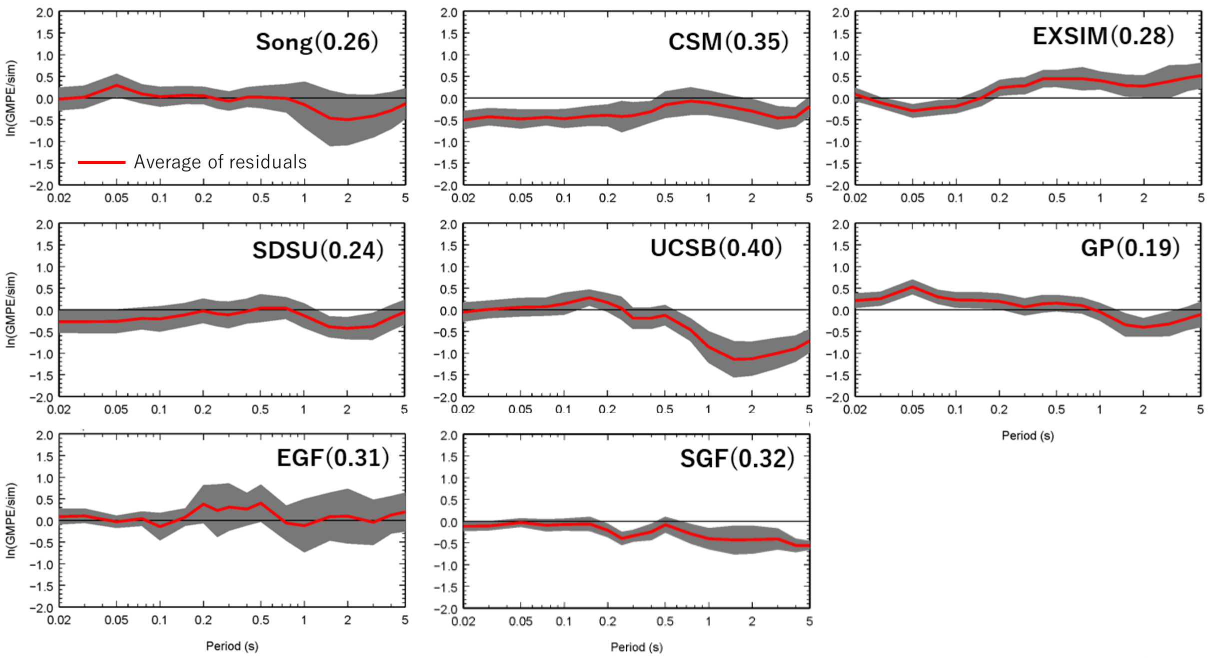
The fault parameters of the characterized seismic source model were set based on the strong motion prediction recipe[36], whereas the seismic moment was given by Irikura and Miyake[45]. For stress drop, the asperity area set to 22% of the fault area and the stress drop on the asperity was set using 3.1 MPa as the average stress drop based on Fujii and Matsu'ura[46]. Ground motion calculations were performed using stochastic Green’s function (SGF) and empirical Green’s function (EGF) methods, using multiple cases of fault models with varying fault slip distributions. For element earthquakes, SGF was constructed based on Boore[47], while EGF was constructed using the observation records of the March

26, 2001 earthquake (No. 6 in Fig. 6), which has different seismic source characteristics but has similar paths to reach the site as earthquakes assumed from the Median Tectonic Line Active Fault Zone so that its propagation characteristics can be used. These records were corrected for density and S-wave velocity based on Dan and Sato[48]. Waveform synthesis was performed using the method by Dan et al.[49]. For SCEC BBP, ground motion calculations using the above six methods (version 16.5.0) were performed using multiple cases of fault models with varying slip distributions of the fault.

Figure 9 shows the calculated 5%-damped pseudospectral acceleration in the horizontal direction (shown using RotD50[35]) and the residuals between the evaluation results based on the simulation and GMPE. Note that to assess the residuals, we used the GMPE by Campbell and Bozognia[50], which is one of the NGA-West equations that had been validated for consistency with observation records and widely used in other countries. Figure 9 also shows the combined goodness-of-fit (CGOF, a metric to quantitatively validate ground motion evaluation results)[51] for each method calculated using Eq. (3), using the evaluation results based on simulation methods and the evaluation results based on GMPE by Campbell and Bozognia[50] obtained for each period.



(a) 5%-damped pseudospectral acceleration



(b) Residuals between simulation evaluation results and GMPE by Campbell and Bozognia[50]
(numbers in parentheses are CGOF)

Fig. 9 Evaluation results from each ground motion simulation method (horizontal direction)

$$CGOF = \frac{1}{2}\left|\left\langle \ln\left(\frac{GMPE}{Simulation}\right)\right\rangle\right| + \frac{1}{2}\left\langle\left|\ln\left(\frac{GMPE}{Simulation}\right)\right|\right\rangle \quad (3)$$

In the equation, the symbols < > indicates the mean and | | the absolute value. According to Fig. 9, although the residuals are slightly larger at periods of 1 s and higher for some of the models, evaluation results using characterized seismic source models may be considered as generally agreeing well with the results using GMPE and SCEC BBP fault models.

Based on the above considerations, in developing the GMC models, we decided to use ground motion evaluations based on characterized seismic source models to represent evaluations based on ground motion simulation using fault models. In assigning weights to the branching between evaluations based on GMPE and evaluations based on ground motion simulation, based on the fact that while GMPE is favored due to its high reliability within the range of the dataset, ground motion simulation using fault models is judged to be superior with regard to applicability to ground motion evaluations near the seismic source. Given that both methodologies have long been used in ground motion evaluations in Japan, both branches were given equal weight. Moreover, in light of the fact that the ground motion levels of ground motion simulations in Fig. 9(a) vary in the range of about 1.5 to 1/1.5 times the average value, we accounted for the epistemic uncertainty in the ground motion simulation method by setting three branches: central value, 1.5 times the central value, and 1/1.5 times the central value. Judging that the results of ground motion evaluations based on characterized seismic source models (SGF and EGF) are at the average ground motion levels of ground motion simulations, and that the reliability of the evaluation results had been sufficiently validated, we set the weight of the central value to 0.8 and equally divided the rest of the weight (0.1) to 1.5 times the central value and 1/1.5 times the central value (point (2) in Fig. 3).

4.3 Evaluation of aleatory variability of ground motion near the seismic source (Point (3))

4.3.1 Analysis of variability near the seismic source

In PSHA, it has been known that the setting of the aleatory variability has a large impact on the evaluation of low frequency earthquakes. With more increasing seismic observation records in recent years, research is being conducted to separate the variabilities due to epistemic uncertainty and aleatory variability from the analysis of variabilities of observation records for ground motion prediction equations (Anderson and Uchiyama[52]), etc.). There is also research on aleatory variability based on earthquake records at the same station (Hikita and Tomozawa[53]), Hikita et al.[54]), etc.). On the other hand, as mentioned previously, there are not enough large-scale, near-source strong motion records to perform high-precision statistical processing and it is currently difficult to quantitatively evaluate the variations in ground motion when the source fault is located near the site based on observation records.

Thus for the Ikata SSHAC Project, we carried out ground motion simulation analysis using fault rupture models for earthquakes on the Iyo-nada Segment of the Median Tectonic Line Active Fault Zone located near the Ikata site and analyzed the variations in ground motion near the seismic source. Based on the study conducted by the SSC TI team, the fault used in the analysis was 54 km long, 2 km deep at the top, and 18 km deep at the bottom, and with dip angles set to vertical and 40 deg north. For the other parameters, two asperities were set in the fault plane using 16 models of varying locations of the asperities in the fault plane, after which the epicenter were set one point at a time on the bottom of each asperity, in order to study the distribution of variations in ground motion without bias. Furthermore, we considered two values of rupture propagation velocities, 0.72 times the S-wave velocity by Geller[55]) and 0.80 times the S-wave velocity by Kataoka et al.[56]), and performed ground motion simulation analyses for 64 cases (16 models x 2 rupture initiation points x 2 rupture propagation velocities) for two models with different dip angles. The procedures for setting the planar position and fault parameters of the Iyo-nada Segment, as well as for the element earthquake and waveform synthesis used for ground motion calculations (SGF) are the same as in the previous section.

Figure 10 shows the source fault locations and ground motion evaluation points used in the analysis, as well as examples of fault rupture models for the vertical case, whereas Fig. 11 shows ground motion simulation analysis results. Figure 11 shows the analysis results for all cases calculated at each evaluation point and the comparison with GMPE using Si et al.[23], the spatial distribution of mean values, the spatial distribution of variations, and the relationship between variation and fault distance, from left to right. Note that the variation is expressed by natural logarithm standard deviation.

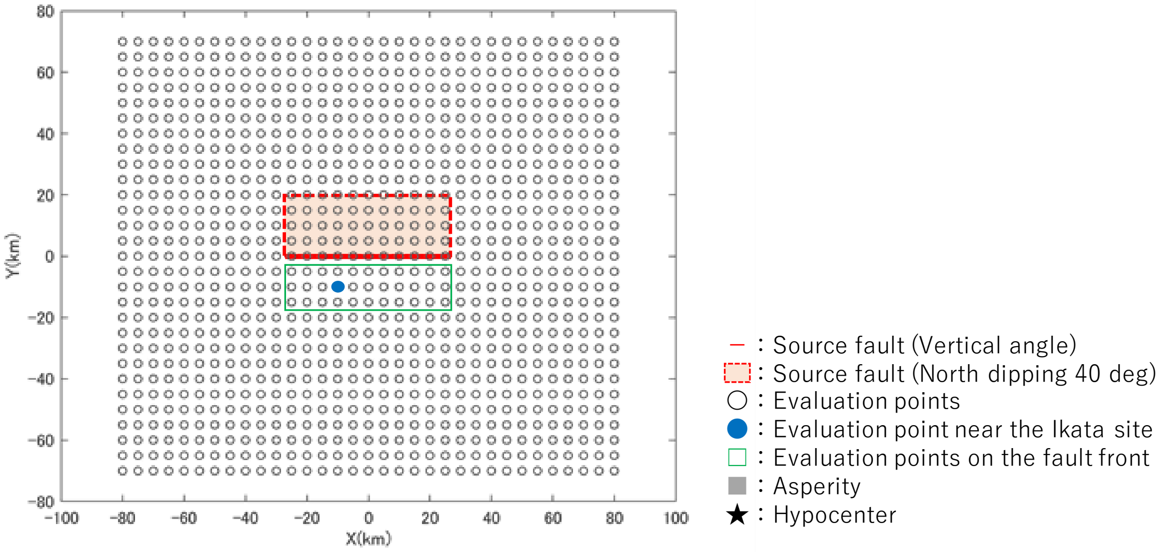
From Fig. 11, it can be observed that the calculated ground motions correspond roughly to the GMPE, and that the spatial distributions of mean values and variations do not exhibit any unusual distribution. For the relationship between variation and fault distance, variations tend to be larger for shorter distances on the short-period side of ground motions, and for longer distances on the long-period side, regardless of the dip angle. For points in front of the fault, although their variation tendencies differ depending on the periodic zone, their variations are roughly similar for the vertical case and north-dipping case compared to the median characteristics of other nearby evaluation points. Focusing on the evaluation point near the Ikata site, its variations are slightly smaller for the north-dipping case and roughly the same for the vertical case compared to the points in front of the fault.

Here, the values of the variance and the type of probability distribution for the PSHA may also be directly calculated from the results of the ground motion simulation analysis. Thus it is possible to quantitatively calculate the finiteness of ground motion levels near the seismic source without assuming probability distributions, such as the lognormal distribution commonly used in PSHA. It is expected that it will be possible to achieve evaluations that consider the source characteristics of MTLAFZ earthquakes as well as specific information such as the relative relationship between the Ikata site and seismic sources. However, given that it is currently difficult to adequately validate the variations based on observation records, we considered it premature in the PSHA to directly use the absolute values of ground motion variations obtained here. On the other hand, we considered that the relative differences in variation between points (points near the seismic source and points far from the seismic source) may be effectively used. In the Ikata SSHAC Project, we analyzed the relative relationship between the variations in ground motion near the seismic source and the variations in ground motion at relatively distant areas, which are the main scope of evaluations based on GMPE and for which there are plenty of observation records. Then we decided that we reflect the variations in ground motion near the seismic source in the logic tree (point (3) in Fig. 3).

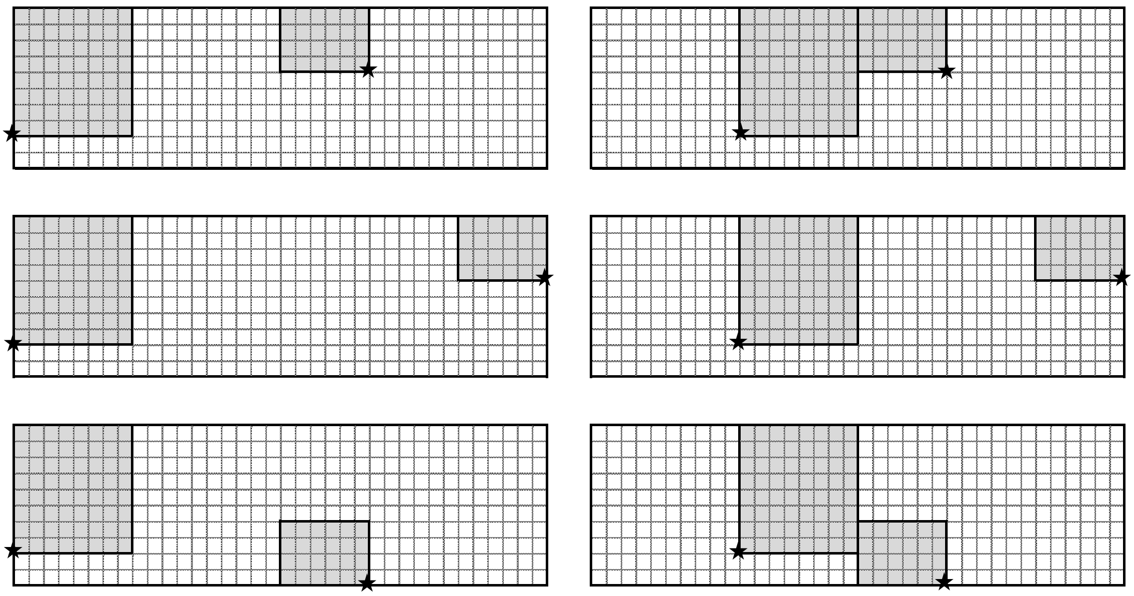
Therefore, in light of the fact that the variations in ground motion on the short-period side are relatively small and stable at distant points with more than 20 km fault distance (Fig. 11), we calculated the ratio of the average value of variations at all points within 20 km fault distance relative to the average value of variations at distant points with more than 20 km fault distance for each period (Fig. 12). Note that in order to focus on variations on the short-period side, which is critical for the seismic performance evaluation of nuclear power plants, Fig. 12 shows the results for periods of 0.6 s or less, with the addition of the results for the period of 0.25 s, which is not shown in Fig. 11. Similar to Fig. 11, the evaluation point near the Ikata site and points in front of the fault are shown separately.

The analysis results revealed that although there are slight differences depending on the period, the ratio of variations near the seismic source relative to distant points is around 1.1 to 1.3 times on average for both points in front of the fault and the evaluation point near the Ikata site. This result is because ground motions at the evaluation points close to the fault are easily affected by the location of the asperities and the setting of the epicenters, and whereas ground motion levels vary greatly depending on whether the rupture progresses through the asperity or in the opposite direction, they are less affected by the difference in asperity locations and epicenters the farther away from the fault.

Based on the above, in the logic tree for variations in ground motion when the seismic source is located near the Ikata site, we set branches that are each 1.2 times the value of three set branches (point (3) in Fig. 3), based on the fact that the values near the seismic source are around 1.2 times the values at distant points on average. Specifically, previous studies (for example, Fujiwara et al.[3]) have shown that the variance of ground motions have a natural logarithm standard deviation with a value of 0.5 on average, although the value varies in the range of 0.4 to slightly over 0.6. Accordingly, we initially set branches with values of 0.4, 0.5, and 0.65 and multiplied each by 1.2 to set branches for 0.48, 0.6, and 0.78.

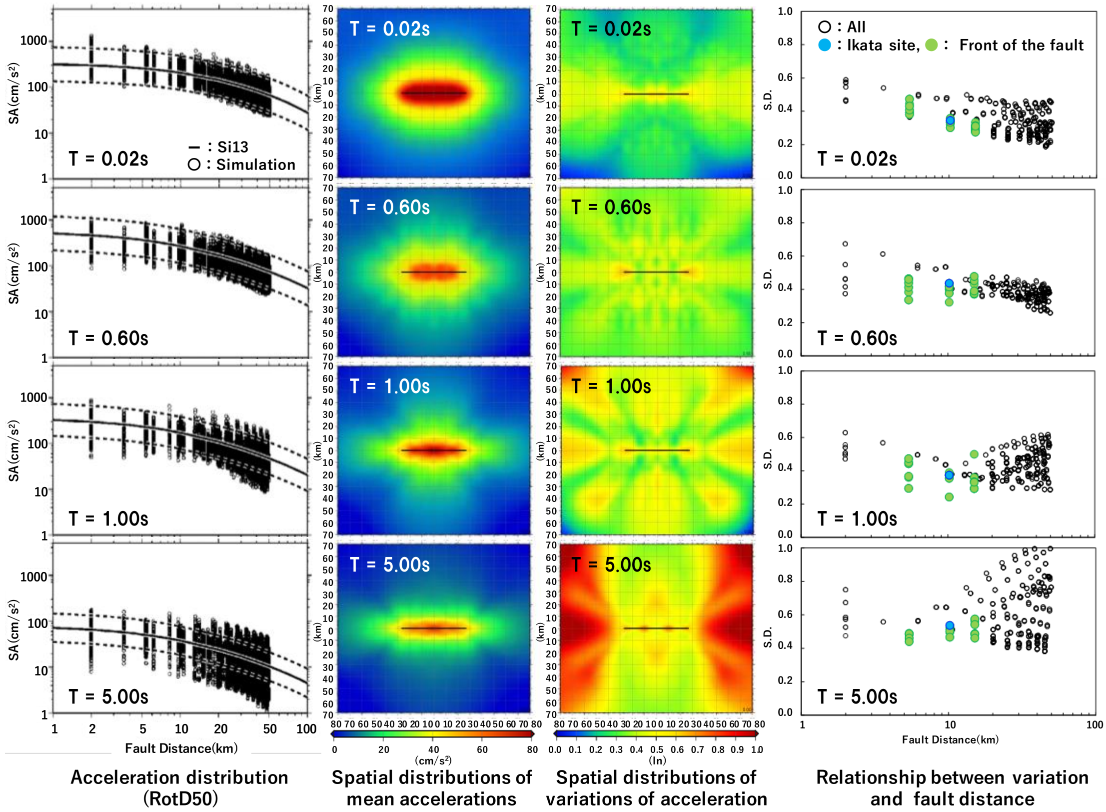


(a) Source fault locations and ground motion evaluation points

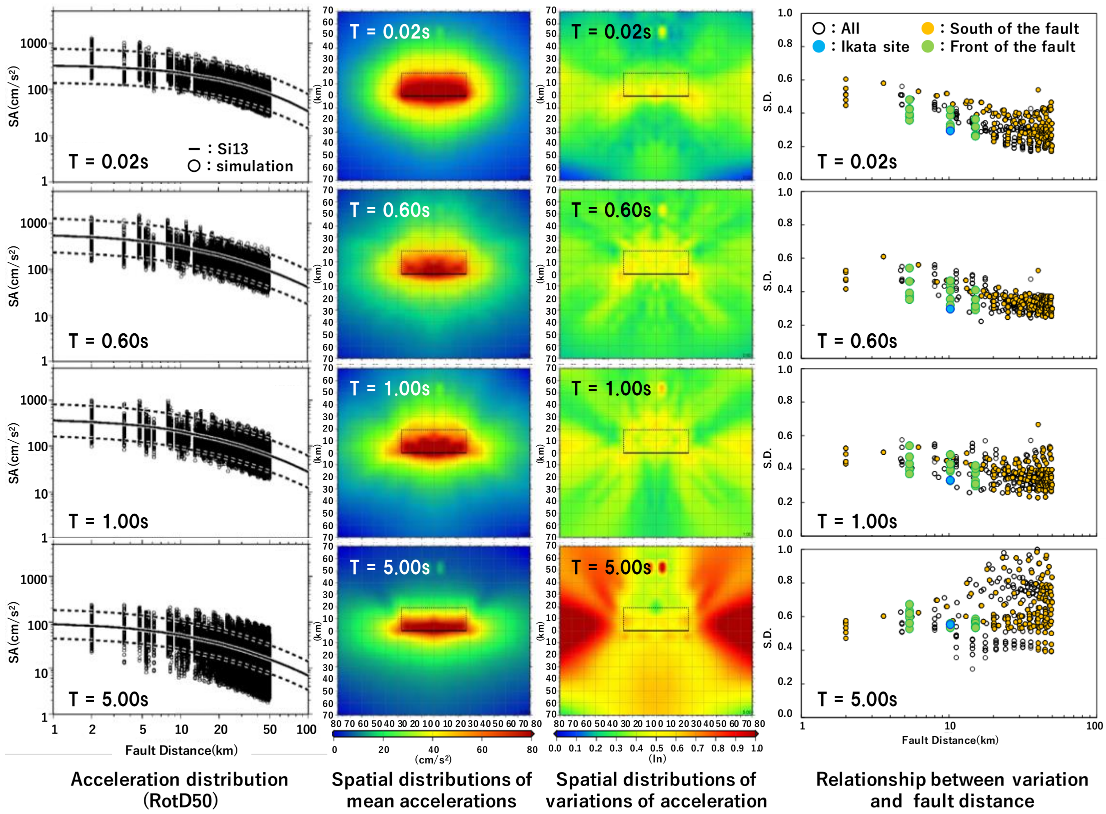


(b) Examples of fault rupture models for the vertical case

Fig. 10 Model for ground motion simulation analysis used to analyze variations in ground motion near the seismic source



(a) Vertical case



(b) North-dipping 40 deg. case

Fig. 11 Ground motion simulation analysis results (horizontal direction)

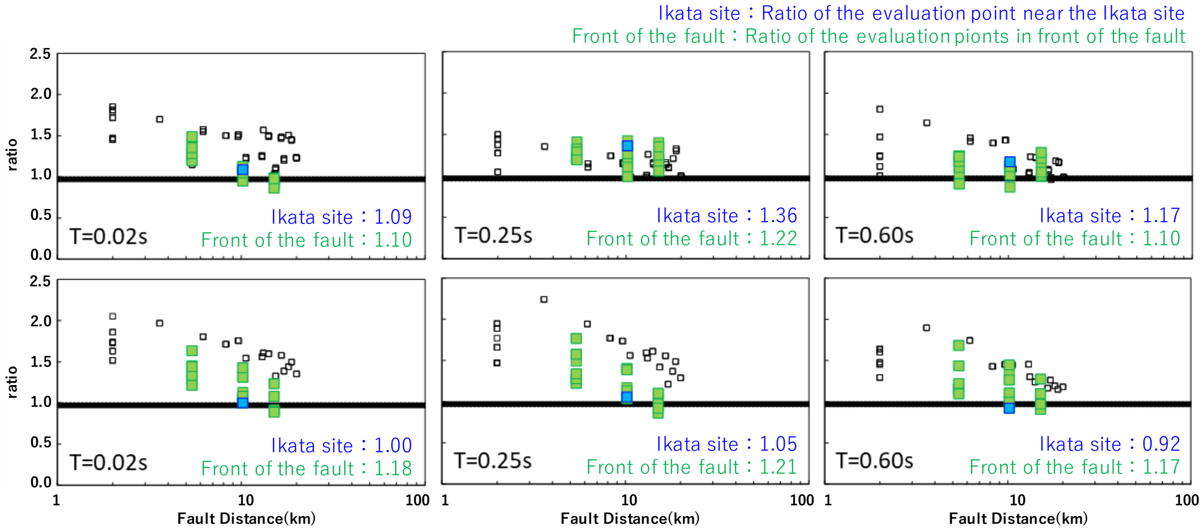


Fig. 12 Variation in predicted values near the seismic source relative to distant points (top row: vertical case, bottom row: north-dipping 40 deg case)

4.3.2 Probability distribution of aleatory variability

For the probability distribution of aleatory variability in natural phenomena such as earthquake motions, a probability density function based on the lognormal distribution is commonly assumed. When a lognormal distribution is assumed, a small probability remains for extremely large ground motion levels at the tails of the distribution. However, ground motion is a finite physical phenomenon, which is considered to have a peak in the actual phenomenon.

Fujiwara et al.[3] used seismic observation records obtained from main shocks and aftershocks of the 2003 Tokachi-oki Earthquake to evaluate variations in ground motion based on the ratio between observed and predicted values, and showed that there are still some data where the variance σ after correcting for site characteristics exceeds the range of ±3σ. Considering that such probability is extremely small compared to the probability levels of the probabilistic seismic hazard maps covering the whole of Japan, data exceeding the range of ±3σ were regarded as statistical anomalies and the tail ends of the lognormal distribution were truncated. The Atomic Energy Society of Japan[57] has determined that since ground motion intensity is phenomenologically finite, the validity range of the lognormal distribution must be set as finite. And if sufficient grounds for setting the truncation range cannot be obtained, then a sufficiently large value (for example, up to five times the standard deviation) may be set, taking into consideration the range of the ground motion acceleration levels that affect the core damage frequency. The Electric Power Research Institute and U.S. Department of Energy[58] stated that although it is common practice in PSHA to truncate the ground motion distribution at a maximum $\varepsilon = 3$ (ε: multiplier from the logarithmic standard deviation) in the Western United States, they found no technical basis for truncating at this level, and concluded that they do not recommend truncating the ground motion distribution based on a maximum value of ε for PSHA. Hanks et al.[59] considered an approach that reflects the upper limit of earthquake response in PSHA from the physical limits to earthquake ground motion, Andrews et al.[60] showed the physical limits of ground motion in the Yucca Mountain, but they found no analysis results to justify the truncation range of 2 or 3 σ. Si et al.[61] studied the distribution of residuals between GMPE and observation records based on the NGA-West2 database and found that the skewness increases in the negative direction with larger earthquake magnitudes (right tail becomes shorter) and that the distribution of residuals deviates from the lognormal distribution (Fig. 13). They concluded that the conventional lognormal distribution can be replaced by an extreme value distribution such as the generalized Pareto distribution.

The earthquakes evaluated at the Ikata site include both seismic sources with relatively low frequency of occurrence but have the potential to cause large ground motions and seismic sources that do not generate such large ground motions but occur at high frequency. In particular, when focusing on low-frequency hazards using the lognormal distribution for high-frequency seismic sources, the possibility of ground motion evaluations that greatly exceed observed levels cannot be ruled out. Hence, according to the findings above, we believe that a distribution that takes peaking into account, such as the generalized Pareto distribution, should ideally be adopted when performing PSHA based on the fact that there is a physical upper limit to earthquake ground motion. However, to date, sufficient data has not been collected or processed for discussion of the appropriate distribution, so this is left as an issue for the future.

Therefore, for the Ikata SSHAC Project, we adopted the lognormal distribution for the distribution of variations in ground motion as a branch of the logic tree. Although we also included a branch for the distribution with a truncated upper limit to consider the finite nature of ground motion and set the weights equally for both, as an initial step to consider the latest findings and work toward resolving issues in the future (point (3) in Fig. 3).

Group	Data Size	Mean	Std Dev	Skewness	Kurtosis
A ($5 \le M_w < 6$)	357	-0.49	0.67	-0.337	0.358
B ($6 \le M_w < 7$)	485	-0.247	0.725	-0.456	1.055
C ($M_w \ge 7$)	177	0.0725	0.563	-1.076	0.904

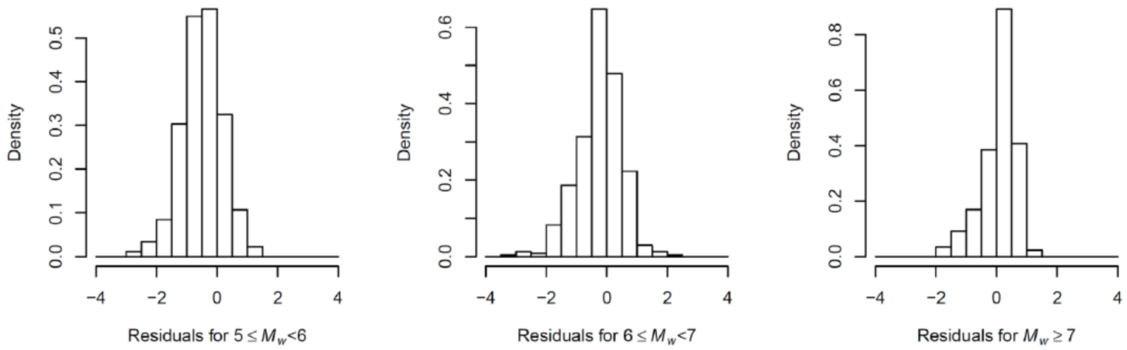


Fig. 13 Probability density histogram of the residuals (natural logarithm of the ratio between seismic observation records and GMPE predictions) for each predicted value of earthquake magnitude (partially modified from Si et al.[61)])

5. SEISMIC HAZARD ANALYSIS

5.1 Hazard analysis results

Figure 14 shows the results of the final hazard analysis. According to the hazard curves by seismic source, for the period of 0.02 s and others on the short-period side, the acceleration level of MTLAFZ earthquakes is the highest, followed by the level of the Nankai Trough Megathrust Earthquakes. In the range of low acceleration levels, blind earthquakes in the Philippine Sea Plate and the Nankai Trough Megathrust Earthquakes with relatively high probabilities of occurrence are dominant, although the effect of earthquakes smaller than characteristic scale can also be seen. On the other hand, blind earthquakes in landward plates and other active intraplate fault earthquakes have a small impact on the overall seismic hazard. For the period of 5 s, the acceleration level of the Nankai Trough Megathrust Earthquakes are also relatively high. Furthermore, according to the uniform hazard spectrum, the annual exceedance frequency (times/year) at which accelerations in the order of several hundred cm/s^2 occur at the Ikata site is approximately 10^{-3} to 10^{-4} and the annual exceedance frequency of large accelerations exceeding 1000 cm/s^2 is about 10^{-5} to 10^{-6}, respectively.

Figure 15 shows the fractile hazard curves. Regardless of the periodic band, the mean hazard curve (calculated as weighted mean) is comparable to the 84% fractile hazard curve. This result may be caused by some branches with extremely high hazard levels affecting the mean hazard in the low frequency range below 10^{-5}, which is discussed in detail in the next section.

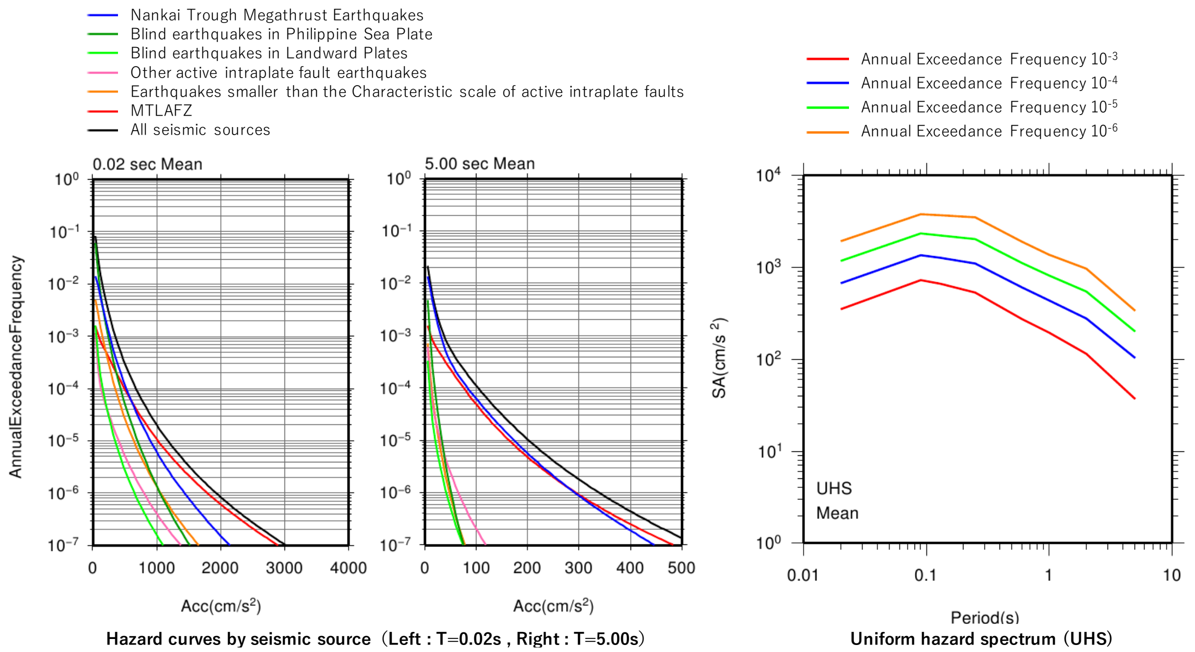


Fig. 14 Seismic hazard analysis results (horizontal direction)

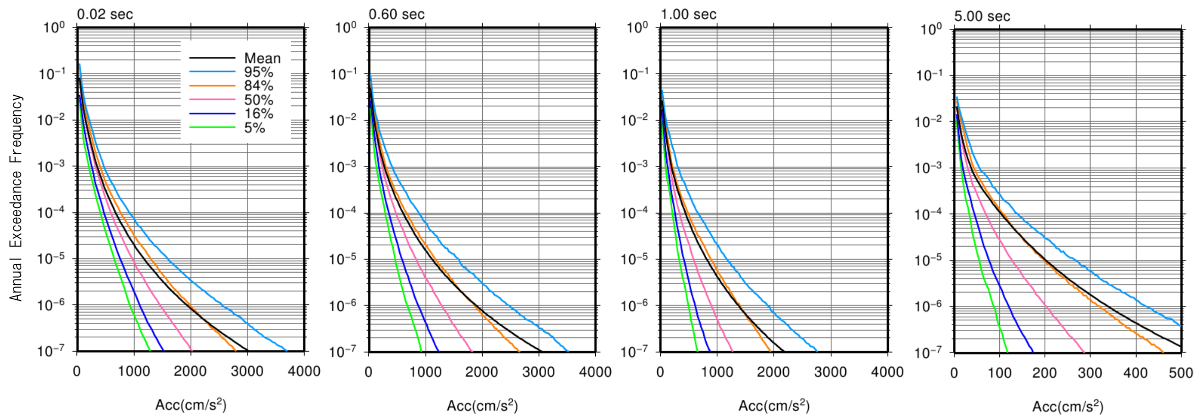


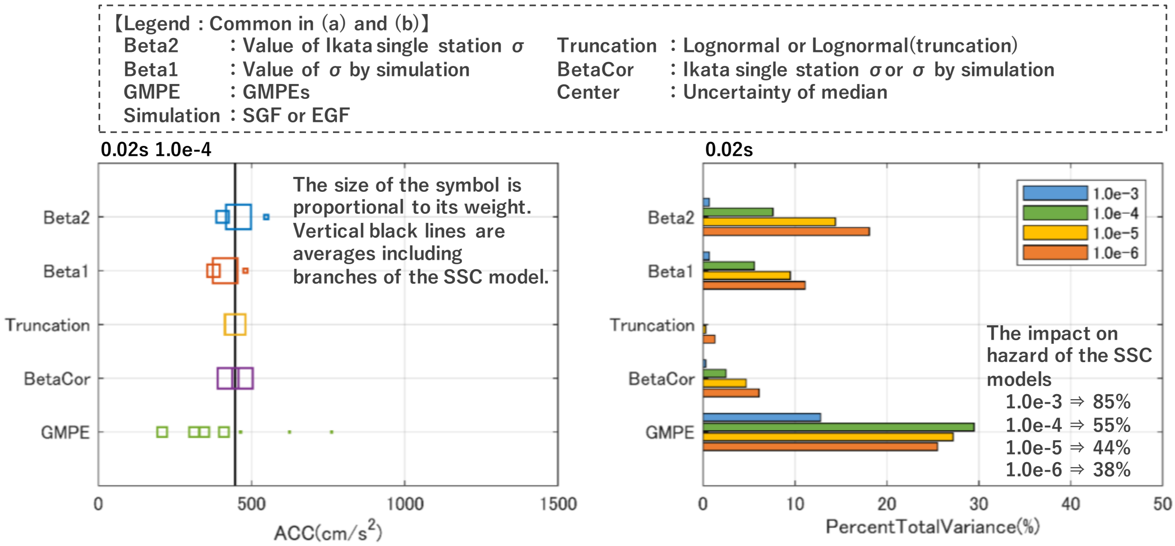
Fig. 15 Fractile hazard curves (horizontal direction)

5.2 Sensitivity analysis results

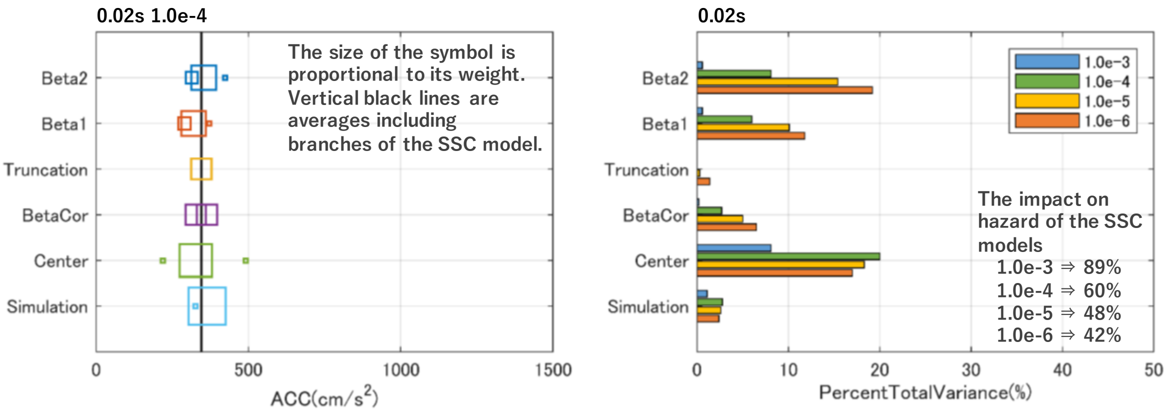
5.2.1 Comparison of evaluations based on GMPE and ground motion simulation

To show the effect on hazard analysis results of epistemic uncertainty in the developed model, Fig. 16 shows an example of a comparison between ground motion evaluation methods based on GMPE and based on ground motion simulation for MTLAFZ earthquakes. The tornado plot[62] shown on the left side of Fig. 16 shows the mean hazard value of each branch of the logic tree, making it possible to check the acceleration levels for each branch of the hazard analysis results. The size of the symbol is proportional to its weight. The variance contribution plot[62] shown on the right side of Fig. 16 shows the level of impact of logic tree parameters on the hazard analysis results as a percentage of the total hazard curve range for each exceedance frequency. Hence, the logic tree parameter with greater variation on the tornado plot is expressed as having a greater percentage (greater impact on overall hazard) on the variance contribution plot. Note that the tornado and variance contribution plots in the figure are for the GMC models and the sum of percentages for each exceedance frequency of the parameters in the variance contribution plot does not total 100% (the remaining amount to reach 100% represents the impact on hazard of the SSC models; actual amounts are shown in each figure).

For the ground motion evaluation method based on GMPE (Fig. 16(a)), the variation in acceleration levels due to GMPE is large and the impact on the mean hazard is large. For GMPE, all the plots that show values greater than the mean hazard are those with small weights; in other words, these are GMPEs with smaller upper limits of the applicable range of S-wave velocity than that of the ground at the Ikata site (UM06[19], KS06[20] and ST08[21] equations), and the plots show that their evaluation results affect the mean hazard. For the ground motion evaluation method based on ground motion simulation (Fig. 16(b)), evaluations were carried out for both the case where the element earthquake is based on SGF and the case where the element earthquake is based on EGF, but the difference between the two was not large. Moreover, in light of the variations in ground motion levels of ground motion simulations shown in Fig. 9 (the fact that the ground motion levels varied in the range of about 1.5 to 1/1.5 times the average value), the plots show the impact of the three branches (central value, 1.5 times the central value, 1/1.5 times the central value) corresponding to the uncertainty in the central value that was set. Although, it is not as large as the impact of the differences in GMPE.



(a) Ground motion evaluation method based on GMPE



(b) Ground motion evaluation method based on ground motion simulation

Fig. 16 Example of tornado plot (left) and variance contribution plot (right) for MTLAFZ earthquakes (horizontal direction)

Next, Fig. 17 shows a comparison of the mean hazard curves for MTLAFZ earthquakes. The logic tree for MTLAFZ earthquakes has two branches, one that includes and another that excludes the Iyo-nada Segment located offshore of the Ikata site. For the case including the Iyo-nada Segment, two types of weighted branches were set: evaluation based on GMPE (red line in the figure) and evaluation based on ground motion simulation (blue line in the figure) (Fig. 3). The mean hazard curve that integrates their weighted means as well as the case excluding the Iyo-nada Segment (green line in the figure) corresponds to the "overall" (black line in the figure) curve in the figure. The hazard curves are large for earthquakes that include the Iyo-nada Segment offshore of the Ikata site, whereas for earthquakes that exclude the Iyo-nada Segment, the impact can only be observed in areas where acceleration levels are very small. Comparing the results from GMPE and ground motion simulation, the acceleration levels are roughly the same on the short-period side (0.02 s and 0.6 s periods). At a period of 1.0 s, the acceleration level for the GMPE is larger, while at a period of 5.0 s, the ground motion simulation is larger. This difference may be attributed to the fact that ground motion simulations are evaluated by simulating the fault rupture process in detail by setting parameters in the microscopic scale, which are not set with GMPE.

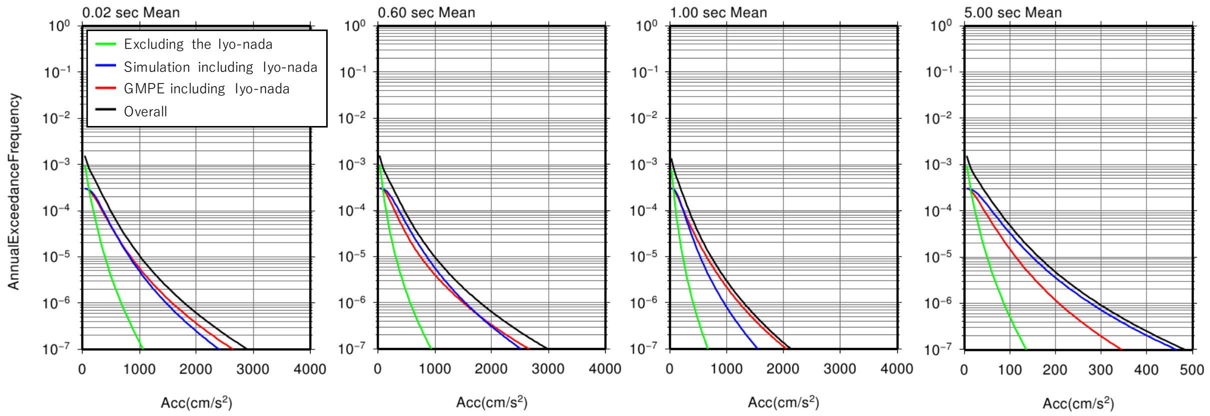


Fig. 17 Comparison of mean hazard curves for MTLAFZ earthquakes (horizontal direction)

5.2.2 Comparison of evaluations based on the probability distribution of ground motion variations

In this section, the effects of aleatory variability on hazard analysis results are presented for the Nankai Trough Megathrust Earthquakes, which has a high probability of occurrence, thus making it a seismic source whose impact levels can be easily assessed. Figure 18 shows a comparison of the hazard curves for all branches of the logic tree that is color-coded according to whether the lognormal distribution is truncated or not, while Fig. 19 shows a comparison that is color-coded according to the values of the variance.

For the GMC models of the Nankai Trough Megathrust Earthquakes, the ground motion evaluation method is based on GMPE. In evaluation results using GMPEs that are normally considered inapplicable due to the ground conditions at the Ikata site as well as GMPEs that are inapplicable to M 9-class earthquakes, a small probability is given even for extremely large ground motion levels that exceed actual earthquake phenomena. In addition, because the Nankai Trough Megathrust Earthquakes has a high probability of occurrence, whether the lognormal distribution is truncated or not and the values set for the variance have a large impact on the hazard particularly at low frequencies and long periods, and the hazard becomes markedly large when the variance is set to 0.65.

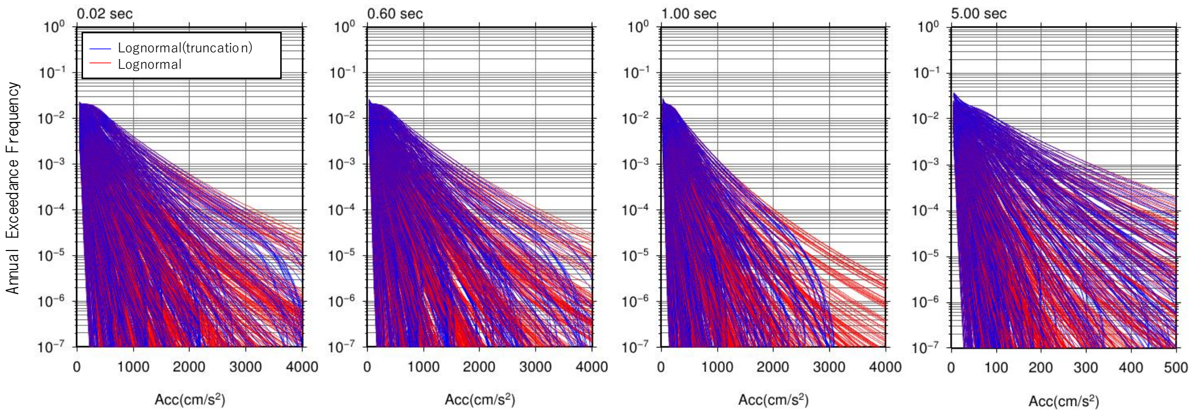


Fig. 18 Comparison of hazard curves according to whether the lognormal distribution is truncated or not for the Nankai Trough Megathrust Earthquakes (horizontal direction)

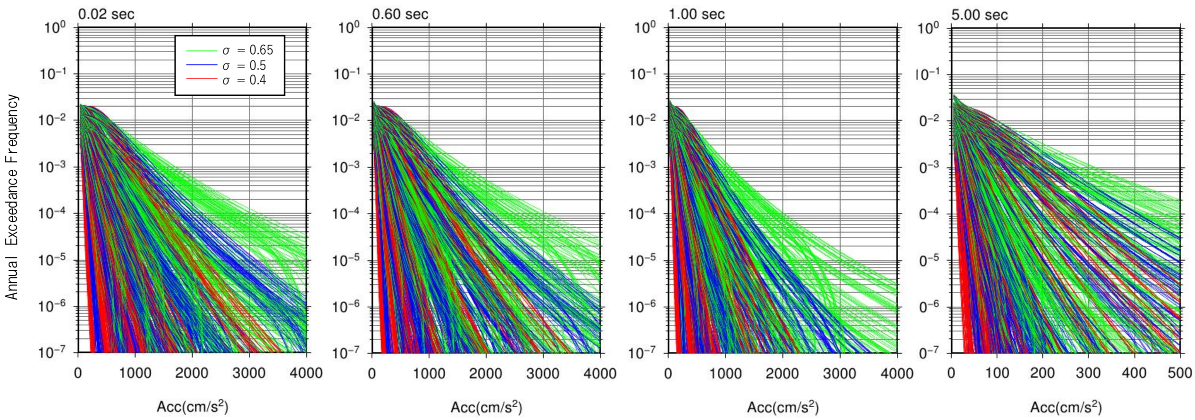


Fig. 19 Comparison of hazard curves according to variance values for the Nankai Trough Megathrust Earthquakes (horizontal direction)

6. DISCUSSION

As discussed in the previous sections, the GMC TI team aimed to develop models that can take into account that the Ikata site is in the proximity of the long active fault of the Median Tectonic Line Active Fault Zone, is located at the northern limit of the assumed focal region of the frequently occurring Nankai Trough Megathrust Earthquakes, and that its grounds are hard enough to correspond to seismic bedrock. Based on the opinions of outside experts and others, a wide variety of studies were conducted, including those adopting ground motion simulation using fault rupture models, those performing GMPE site correction, and those assigning branch weights, to construct logic trees that capture the CBR of TDI. During the development, to the extent possible we worked to implement PSHA studies that consider a wide variety of uncertainties found in natural phenomena, such as by selections that capture the edge of the range, which includes GMPEs considered to be outside of their application scope, from the standpoint of considering the uncertainty of the center.

On the other hand, of the PSHA studies carried out by the Ikata SSHAC Project, we found that the ground motion evaluation based on GMPE, in particular, still have the problem of large differences in predictions among the GMPEs we selected, even after performing site correction. This may be attributed to differences in their scope of applications, such as different databases and ground conditions, as well as the low accuracy of the site correction caused by the lack of observation records at the Ikata site.

Here, we discuss future challenges in ground motion evaluation based on GMPE based on our experience constructing the GMC models implemented in the Ikata SSHAC Project, with the hope of further advancing PSHA in future studies.

6.1 Developing GMPEs based on a common database in Japan

In Japan, a number of experts are developing GMPEs based on their own databases that differ from each other. Each of them has a different approach to setting parameters related to seismic sources and ground conditions, as well as to their selection of the underlying model and data. The Japan-based GMPEs are not only subject to uncertainties due to GMPE modeling, they also include uncertainties due to the fact that their data standards are not the same. Even records from the same station for the same earthquake have different magnitudes, epicenter distance, ground conditions, etc. depending on the database. For this reason, the Japan-based GMPEs selected for the Ikata SSHAC Project is believed to make the uncertainty of the central value larger. On the other hand, in the United States, although the GMPEs in NGA-West2 have been constructed with structures that have their own originality, their parameters were selected based on the same criteria and they were developed based on a ground motion database whose accuracy had been validated. As an example, Fig. 20 shows a comparison of the predictions from Japan-based GMPEs and NGA-West2 GMPEs. The figure shows that the variation in predictions from NGA-West 2 GMPEs is small compared to the variation in predictions from Japan-based GMPEs.

We look forward to the development of GMPEs in Japan that use a common and accurate ground motion database in the future.

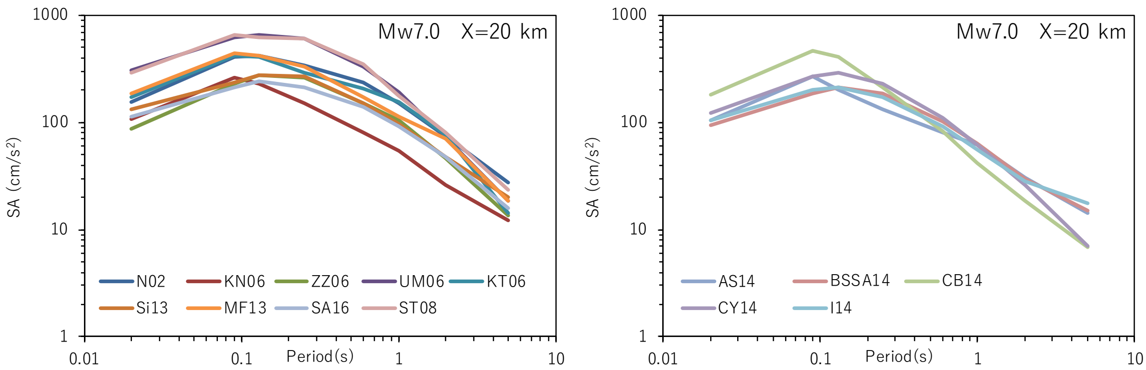


Fig. 20 Comparison of predictions from Japan-based GMPEs (left) and NGA-West2 GMPEs (right) (horizontal direction)

6.2 Improving GMPE site correction

Site corrections were performed on the GMPEs selected for the Ikata SSHAC Project based on seismic observation records, in order to properly evaluate the ground amplification characteristics at the Ikata site. However, most of the observation records that were included were oceanic intraplate earthquakes with small magnitudes; moreover, none of the stations around the Ikata site had ground conditions similar to the Ikata site, resulting in inadequate site correction. A particularly large problem was that the prediction of ground motion levels had large differences between their predicted values even after site correction on the analyses beyond the range of the datasets used for the GMPEs. All of the GMPEs for which deviations were observed had an applicable range of S-wave velocity that is small compared to the S-wave velocity of the ground at the Ikata site. Hence, applying them to the Ikata site remains an issue at present. To be able to use them to accurately evaluate ground motions that occur at individual sites, it is important to compare their results with the evaluation results from other GMPEs and from ground motion simulation using fault models, and carefully examine their applicability.

Going forward, improving the accuracy of site correction will require developing a GMPE that can be applied to sites on hard rock as well as conducting continuous seismic monitoring at the site.

6.3 Applicability to M 9-class large-scale earthquakes and seismic sources near the site

For the Ikata SSHAC Project, M 9-class large-scale earthquakes, such as the Nankai Trough Megathrust Earthquakes, as well as earthquakes with sources located near the site, such as the Median Tectonic Line Active Fault Zone, were assumed and used to evaluate ground motions by using GMPEs. Records of strong motion of large-scale earthquakes with sources located near the site are still insufficient, and there are still issues remaining in the use of GMPEs when evaluating ground motions that are beyond the scope of the GMPE datasets. With regard to application to M 9-class earthquakes, ground motion levels at individual sites peak out even when subjected to large magnitudes; GMPEs that consider this effect have been proposed. However, for other GMPEs, ground motion levels increase with magnitude and M 9-class earthquakes are beyond their range of applications; hence, the accuracy of their predictions, which are in the range of extrapolations, remains an issue. Moreover, since there are no observation records of Nankai Trough Megathrust Earthquakes occurring in the Philippine Sea Plate, validating the applicability of the current GMPEs and developing GMPEs that take into account the characteristics of earthquakes occurring in the Philippine Sea Plate are also issues. Furthermore, with regard to setting and truncating the probability distribution of ground motion variations, the validity of assuming a lognormal distribution even at large amplitudes and the existence of an upper limit for ground motions remain as unresolved issues.

Our future challenge is to expand earthquake observation records for large-scale earthquakes and near seismic sources and to construct GMPEs based on these records. Comparing them with ground motion simulation using fault models will likely be useful as well.

7. CONCLUSIONS

The Ikata SSHAC Project is the first project to use SSHAC Level 3 for the PSHA of a nuclear power plant in Japan. In this paper, we discussed the studies conducted by the project pertaining to the development of GMC models dealing with epistemic uncertainties in ground motion evaluation, particularly on the results of studies related to the evaluation of GMPEs, evaluation based on ground motion simulations using fault models, and evaluation of aleatory variability. We also discussed the technical issues that need to be addressed to further advance PSHA in the future.

In the Ikata SSHAC project, we constructed logic trees that capture the CBR of TDI, in accordance with the guidelines for SSHAC Level 3, for a wide variety of earthquake sources around the Ikata site. The comparative study between the fault models used in our GMC modelling and the models used by the SCEC BBP in the United States was a pioneering effort. We believe that the various findings obtained here are not only significant for the fields of seismology and earthquake engineering, but are also useful for providing a framework for discussions on accurately and objectively evaluating uncertainties, and we hope that they are applied to future studies involving PSHA.

ACKNOWLEDGMENT

In the Ikata SSHAC Project, we used the JMA unified earthquake catalog for the earthquake catalog, K-NET and KiK-net of the National Research Institute for Earth Science and Disaster Resilience for the ground motion database, and earthquake observation records from JMA and the Port and Airport Research Institute. During the project implementation, over 50 experts in and out of Japan provided valuable information and joined the discussions, as well as allowed us to use their lecture materials as databases for model development. The SSC TI team led by Dr. Takashi Kumamoto, developed the seismic source characterization models that are a prerequisite for evaluating the ground motion. From the five members of the PPRP (Dr. Kojiro Irikura serving as PPRP Chair, Dr. Atsumasa Okada, Mr. Tadashi Annaka, Dr. Ken Ugada, and Dr. Martin McCann Jr.) we received the necessary feedback and comments to ensure that we followed the requirements of SSHAC Level 3 throughout the project, as well as a thorough and appropriate review of the final report draft. Both Dr. George Apostolakis and Dr.

Kevin Coppersmith joined as experienced SSHAC advisors and provided valuable advice on both procedural and technical aspects throughout the project. Project management was carried out by the Central Research Institute of Electric Power Industry and Ceres, Inc. The seismic hazard analysis was conducted by Ohsaki Research Institute, Inc. and Kozo Keikaku Engineering, Inc. We express our deepest gratitude and appreciation to all of the people mentioned above.

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