Uncertainty analysis relevant to the fault rupture modeling method

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Abstract. Both the conventional ground motion prediction equation method and the physics-based fault rupture modeling method have been used for ground motion evaluation to define design basis ground motions for nuclear power plants in Japan since 2006. This paper introduces our research projects on the fault rupture modeling method, compares the scaling law applied in the fault rupture modeling method with the new data from recent earthquakes, and addresses uncertainty analysis especially in near-source ground motion evaluation. Our research results show that the new data are consistent with the scaling laws proposed by previous studies. It also suggests that the fault rupture modeling method deals well with near-source issues when the evaluation site is several kilometers away from the fault source. Furthermore, the study results of the 2016 Kumamoto earthquake show that, even for the sites with a fault distance of less than 1km, the method works well as far as the short-period ground motions are concerned, whereas observed ground motions at long periods can be well simulated by taking into account the rupture in the shallow portion of the fault.

Key Words: design basis ground motion, fault rupture modeling, uncertainty analysis.

1. INTRODUCTION

As an earthquake-prone country, Japan has paid particular attention to seismic issues in the location, design and construction of nuclear power plants (NPP). A former regulatory guide issued by the Atomic Energy Commission in 1978 [1] required the formulation of two levels of design basis ground motions (DBGM), i.e., S1 for the maximum earthquake and S2 for the extreme case; the latter was used for the seismic design of important safety related structures, systems and components. The Nuclear Safety Commission (NSC) [2] revised the guide in 2006, integrating S1 and S2 into a single level (hereinafter referred to as “the DBGM Ss”, though literally named “standard seismic motion Ss” [3]). The 2006 NSC regulatory guide required that the DBGM Ss should be determined by considering the following two types of ground motions, ‘site-specific ground motions evaluated by specifying seismic sources’ and ‘ground motions evaluated without specifying seismic sources’. As a major revision of the regulatory guide, in the case of ‘site-specific ground motions evaluated by specifying seismic sources,’ the physics-based fault rupture modeling method shall be applied in addition to the conventional ground motion prediction equation (GMPE) method (literally, *the response spectrum method*).

In light of the lessons learned from the 2011 Tohoku earthquake, the Nuclear Regulation Authority (NRA) issued a new regulatory guide [4] in 2013. In the 2013 NRA guide, the regulatory standards regarding earthquake design are enhanced, for example, more precise methods are required to be applied to define DBGMs by considering the effects of the three dimensional structures, if necessary. In particular, when the identified capable fault is very close to the site, a source model characterized by a whole-fault rupture and surface faulting shall be considered and the uncertainties of ground motion evaluation be analysed in detail such that the DBGMs are appropriately defined.

In response to the new regulatory standards, the Secretariat of NRA has conducted several earthquake-related projects, including projects on dating methods for fault activity assessment, fault displacement evaluation methods, and the fault rupture modeling method for deterministic and probabilistic seismic hazard analysis (hereinafter referred to as “the S/NRA/R projects”). After a brief explanation of the procedure outline applied for developing the DBGM Ss in Chapter 2, this paper introduces the research projects on the fault rupture modeling method, compares the scaling laws applied in this method with the new data from recent earthquakes, and addresses uncertainty treatment in near-source ground motion evaluation. It is worth noting that, though this paper focuses on the uncertainty treatment to be considered in the deterministic approach, a study on application of the new data to the probabilistic analysis is also undergoing.

2. Process of DBGM Development

The process of DBGM development mainly consists of (i) investigation, (ii) seismic source identification, (iii) source characterization, and (iv) ground motion evaluation (FIG.1). To identify seismic sources significant to the seismic hazard for a site of interest, the utilities are required to carry out detailed geological, geophysical, seismological, and geotechnical investigations [4]. The identified seismic sources are further classified into specified fault sources and non-specified fault sources, and different methods shall be applied to evaluate the ground motions for the seismic sources of interest. Note that the non-specified fault sources are comparable with diffuse seismicity defined by IAEA guide [5], but the ground motions are evaluated on the basis of analysis of ground motion data recorded in selected earthquakes supposed to be difficult to specify their source in advance. This approach is unique to Japan because of its high seismicity and plentiful ground motion data.

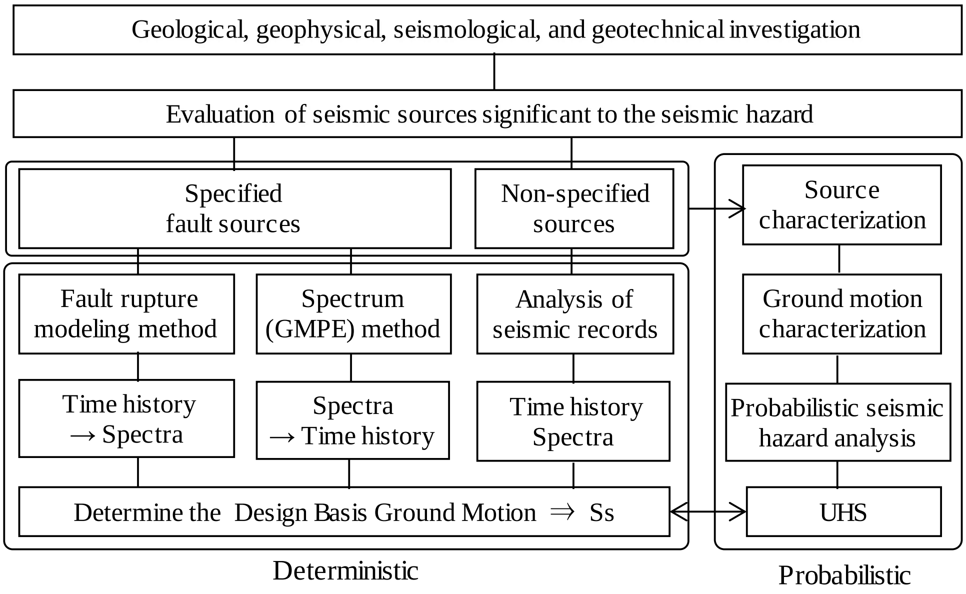


FIG. 1. Flowchart of DBGM development

For the specified fault sources, both the fault rupture modeling method and GMPE method are applied. This fault modeling method, based on the concept of an asperity model and known as the Recipe in Japan [6], is a summary of ground motion simulation studies[e.g., 7-9] and has been used for the scenario earthquake shaking maps of the Japanese National Seismic Hazard Maps. The difference between the method used in Japan and other fault rupture modeling methods proposed outside of Japan can be referenced in the IAEA safety report [10].

As FIG. 1 shows, although the methodology used to develop the DBGM Ss is deterministic, probabilistic seismic hazard analysis (PSHA) should also be conducted and the PSHA results, uniform hazard spectra (UHS) typically with annual exceedance probability of 10^{-6} to 10^{-4}, are required to be presented for reference.

3. Outline and Interim Results of S/NRA/R Projects

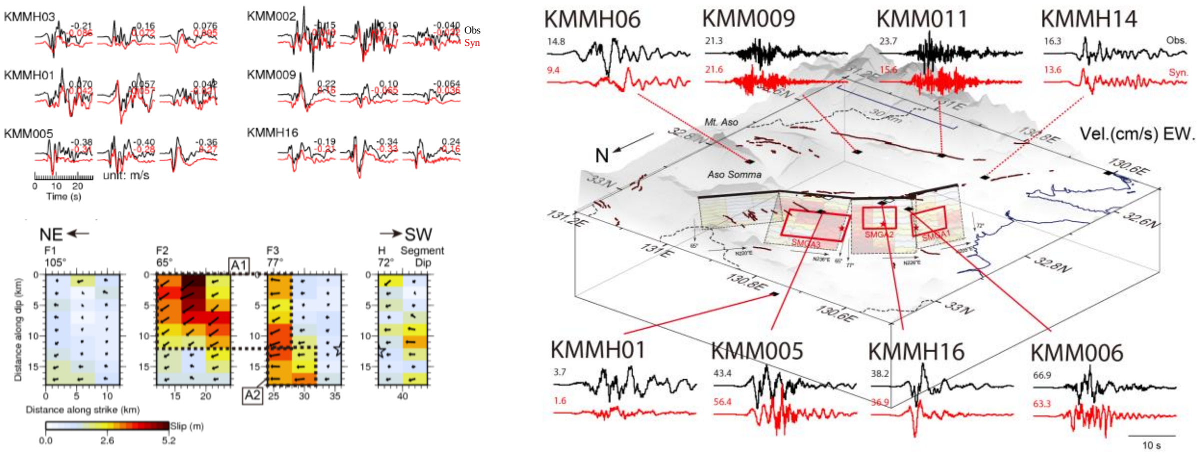
As a tectonically active plate boundary region, Japan has experienced not only major or mega earthquakes in the subduction zone (hereinafter referred to as "subduction zone earthquakes") but also disastrous events occurring in continental crust (hereinafter referred to as "continental earthquakes"). The activity of continental earthquakes has reached a significantly high level since the 2011 Tohoku earthquake. In 2016 alone, for example, we experienced five continental earthquakes with moment magnitude larger than 6.0, among which the Kumamoto earthquake struck the middle area of Kyushu Island on April 16, 2016, following an Mw 6.1 foreshock on April 14 (Table 1). The earthquake sequence caused severe damage and the overall loss ranked third after the 2011 Tohoku earthquake and the 1995 Kobe earthquake.

TABLE 1: List of continental earthquakes analyzed in the S/NRA/R project

Events	Magnitude	Slip sense
2016 Kumamoto earthquake (April 16)	Mw7.0	Strike slip
2016 Fukushima-ken Oki earthquake	Mw7.0	Normal
2008 Iwate-Miyagi Inland earthquake	Mw6.9	Reverse
2011 Fukushima-ken Hamatori earthquake	Mw6.6	Normal
2011 Nagano-ken Hokubu earthquake	Mw6.2	Reverse
2014 Nagano-ken Hokubu earthquake	Mw6.2	Reverse
2016 Tottori-ken Chubu earthquake	Mw6.2	Strike slip
2016 Kumamoto earthquake (April 14)	Mw6.1	Strike slip
2016 Kumamoto earthquake (April 15)	Mw6.0	Strike slip
2016 Ibaraki-ken Hokubu earthquake	Mw5.9	Normal
2013 Tochigi-ken Hokubu earthquake	Mw5.8	Strike slip
2013 Awaji Island earthquake	Mw5.8	Reverse

Aiming to improve the methodology of fault rupture modeling, especially the uncertainty analysis of ground motion evaluation, the S/NRA/R project had carried out systematical analyses of recent continental earthquakes since 2014. This project has been commissioned to the Geo Research Institute, Osaka, Japan. Up to the end of the 2017 fiscal year, 12 earthquakes are systematically analyzed (Table 1). Waveform inversion, strong motion simulation using the strong motion generation area (SMGA) modeling [11, 12], and fault rupture model parameter analysis [13] have been conducted for each earthquake listed in Table 1.

FIG. 2 shows an example of a finite fault model from conventional waveform inversion and strong motion simulation from SMGA forward modeling for the 2016 Kumamoto earthquake. To avoid over-estimating the fault size, waveform inversion is performed in two steps. In step one, a preliminary fault plane is estimated from aftershock distribution and slip distribution inverted from the observed K-NET and KiK-net [14] seismograms which are low-pass filtered at a cutoff frequency of 0.5Hz. This finite fault model is trimmed following the approach proposed by Somerville et al. [15]. In step two, the size of the trimmed finite fault is used and the strong motion data are low-pass filtered at a cutoff frequency of 1Hz. Slip distribution is then inverted as the final result as shown in FIG. 2(a). SMGAs are set in or around the high slip rate areas of the finite fault model and the parameters such as rise time, stress drop, rupture velocity and so on, are adjusted step by step such that a good matching between the observation and synthetic waveforms is reached (FIG. 2(b)). Estimates of SMGA parameters (e.g., stress drops of 13.4 and 13.6 MPa) are similar to those of continental earthquakes. The simulation results indicate that the fault rupture modeling method deals well with near-source issues when the evaluation site is several kilometers away from the fault. It is worth noting that the KMMH16 station is very close to a surface rupture trace (with a distance of about 600m from the surface trace) and the observation motion (black lines in FIG. 2(b)) is well reproduced. This suggests that, even for those sites with a fault distance of less than 1km, the method works well as far as the short-period ground motions are concerned.



(a) Finite fault model from waveform inversion (b) Strong motion simulation from SMGA forward modeling

FIG. 2. Finite fault model from waveform inversion and strong motion simulation from SMGA forward modeling for the 2016 Kumamoto earthquake [12]

The Kumamoto earthquake not only generated strong shakings in a wide area, but also was accompanied with a long trace of surface rupture (e.g., reportedly 34km long [16]). In addition to the KMMH016 station, there are another two stations (denoted as 93048 and 93051 in FIG.3b) located within a distance of 1km from the surface trace. These two stations are operated by the local government for intensity observation and the records are available on the web site of the Japan Meteorological Agency (JMA). As shown in FIG. 3b (black lines), large permanent displacements could be identified through double integrations from the original acceleration records with special attention paid to baseline correction to remove the transient base-line drift which occurs when the ground acceleration exceeds a certain value, typically, about 100cm/s^2. Since the Recipe mainly pays attention to SMGAs, which have been shown to account for short-period strong ground motions [11], contribution to long-period components from the shallow rupturing (e.g., the blue areas in FIG. 3a) has been neglected. As FIG. 3 shows, the long-period ground motions can be well simulated by adding long-period motion generation areas (LMGA) in the shallow portion to the conventional SMGA model.

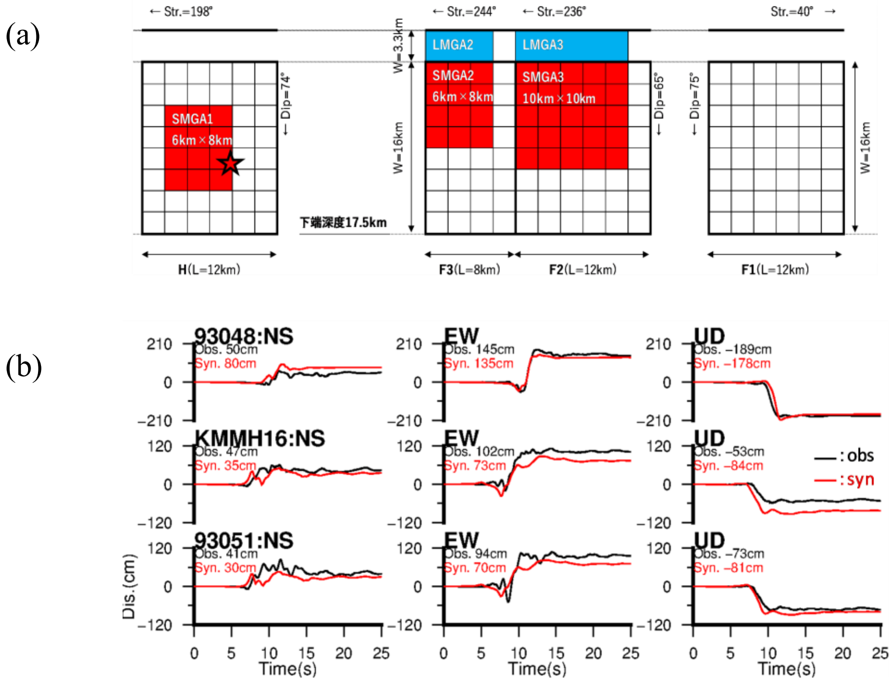


FIG. 3. (a) A long-period motion generation area model and (b) comparison of observation and synthetic waveforms at the three sites close to the surface rupture of the 2016 Kumamoto earthquake.

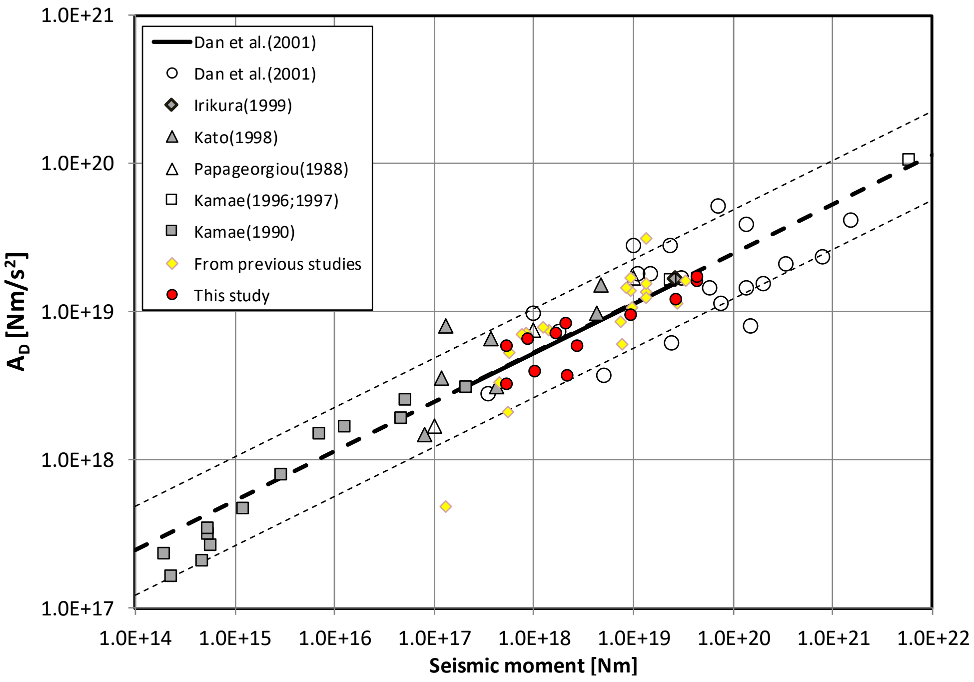


FIG. 4. Relationship of short-period source spectrum level with seismic moment. The solid black line means the values predicted by the formula of Dan et al. (2001), and the dashed lines mean twice and half the prediction.

Fault and SMGA parameters obtained in this project or previous studies are also analyzed and compared with the scaling laws used in the Recipe [9]. To show an example of parameter analysis, FIG. 4 plots the values (red solid circles, corresponding to events in TABLE 1) of short-period source spectral level (A_D) estimated from SMGA results (following the method of [9]) against seismic moment (M_o). Our interim results indicate that A_D is proportional to $M_o^{1/3}$, consistent to the scaling law (solid black line in FIG. 4) used in the Recipe. Note that the A_D estimates show a relatively small variation from the scaling law, indicating a small variation of stress drops of the asperities.

4. Uncertainty Treatment

Following the terminology of the Senior Seismic Hazard Analysis Committee [17], we classify uncertainty as epistemic uncertainty and aleatory variability. Epistemic uncertainty is usually attributable to the limitation of our current knowledge and hence reducible through the acquisition of more data in the future, whereas aleatory variability is irreducible within the framework of a model and treated as the inherent randomness of a process to be modeled. It is worth pointing out that the distinction between the two categories of uncertainty depends on not only the context of modeling but also its application [18]. Given the seismic moment of a target earthquake, most fault parameters (e.g., stress drop, slip distribution and rupture velocity) in the Recipe are determined from empirical scaling laws and some theoretical formulae. By gathering more data in the future, the scaling law may be improved and the theoretical formula refined such that the epistemic uncertainty in the estimation of fault parameters can be reduced. Abrahamson et al. [19] categorized this kind of parameter as fixed parameters and its uncertainty as modeling uncertainty in contrast to free parameters (e.g., rupture starting point and location of asperity) and associated parametric uncertainty. On the other hand, variation of the fault parameters mentioned above for an individual earthquake is outside the current framework of the Recipe. If the fixed parameters are treated as event-to-event variables in the validation of the Recipe, the deviation between the observation and simulation ground motions might be apparently reduced. From the viewpoint of prediction issue, however, this does not mean that the total uncertainty is reduced because it is impossible to precisely predict those fault parameters for a future earthquake in advance.

TABLE 2: Categorization of uncertainties

	Epistemic Uncertainty	**Aleatory Variability**
Modeling Uncertainty	Probabilistic model uncertainty: *e.g., log-normal/Gamma/Weibull distribution in PFHDA*	
	GMPE*:* σ_μ (*uncertainty in the prediction* μ) σ_σ (*uncertainty of the variation* σ)	σ_{AM} *(unexplained variation due to physical processes not considered in the model)*
	Physics-based simulation: *Uncertainty in characterization of physical processes included in the model, e.g., uncertainty in source* (*Asperity/hybrid/composite models,* <u>*the values of fixed parameters*</u>), *ground motion* (*SGF/EGF*) *modeling, etc.*	
Parametric Uncertainty	GMPE: σ_μ (*uncertainty in median values of parameters*) σ_σ (*uncertainty in distributions of parameters*)	GMPE*:* σ_{AP} (*event-to-event variation in parameters*)
	Physics-based simulation: *Uncertainty in probabilistic distributions of free parameters* (*e.g., whether rupture starting point tends to be confined in deep portion of fault*)	Physics-based simulation: *Event-to-event variation in free parameters* (*e.g., rupture starting point*)

Further consideration of uncertainty categorization and the distinction between GMPE and simulation methods like the Recipe are summarized in TABLE 2. Detailed classification and its implications can be referenced in Toro et al. (1997) [20] and Strasser et al. (2009) [21]. It is worth noting that uncertainty in selection of a probability distribution model should be taken into consideration, especially in the case of fault displacement hazard analysis. Unlike ground motion characterization in which a log-normal distribution is generally used, different distribution models (e.g., Gamma distribution, Weibull distribution, and log-normal distribution) have been applied in different studies [e.g., 22~24].

Effects of modeling uncertainty on ground motion evaluation are analyzed from the viewpoint of a deterministic approach as follows. Based on the modeling results of this project as shown in Chapter 3 as well as those of previous studies, the distributions of fault parameters are modeled. A reference fault model is constructed following the characterization method described in the Recipe. For the six selected parameters as shown in the left side of FIG. 5, uncertainty models with a value of medium ±σ for each parameter are respectively built. The ratios of response spectra from each uncertainty model to those from the reference model are compared for each parameter. In FIG. 5, ratios averaged from 352 evaluation sites of fault distance 5~20 km are plotted from top to bottom in decreasing contribution rank of the six parameters [25]. Note that the contribution rank depends on the period of interest, for example, stress drop of the asperity ranks first for short-period (0.05~02 s) components (FIG. 5a), whereas rise time ranks first and stress drop fourth for relative long-period components (FIG. 5b). Horizontal error bars shown in FIG. 5 indicate the variability from site to site. For example effects of asperity depth are more significant for near-fault sites than sites with a larger fault distance.

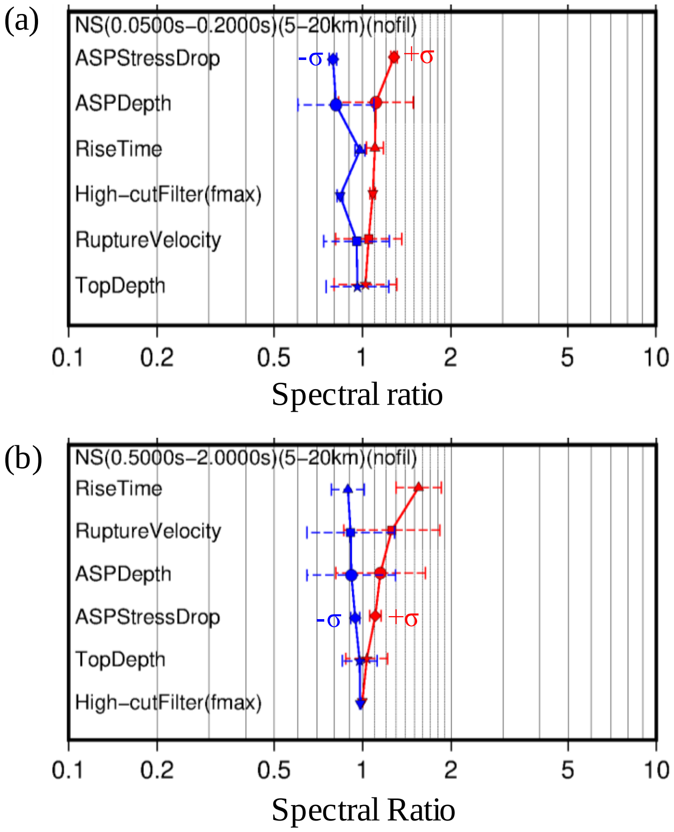


FIG. 5. Ranking of effects of uncertainties in parameter estimates on ground motion simulation [26]. Spectral ratios are averaged in period ranges of (a) 0.05~0.2 s and (b) 0.5~2 s, respectively. Red marks mean a positive effect on ground motion and blue marks a negative effect.

The fault rupture model discussed above is based on the concept of an asperity model where the fault rupture is characterized as a background area with low stress drop and smaller slip, as well as asperities with higher static stress drop and larger slip (hereinafter referred to as “IM model”) [8]. In contrast to the asperity model, Graves and Pitarka [26] use a stochastic model where heterogeneity of slip distribution is taken into account (hereinafter referred to as “GP model”). Besides the GP and IM models which are constructed on the basis of the kinematic rupture model of the Kumamoto earthquake, this study (Pitarka et al. [27]) generated a new rupture model (“IM-GP model”) which integrates desired features of the above two end-number models. FIG. 6c shows the goodness-of-fits for three models in terms of the bias of mean spectral acceleration response, i.e., RotD50 [28], between recorded and synthetic ground motion, averaged over all stations. Generally speaking, all three models performed satisfactorily in simulations of recorded ground motion and the IM-GP model made a slightly better simulation in both short- and long-period ranges.

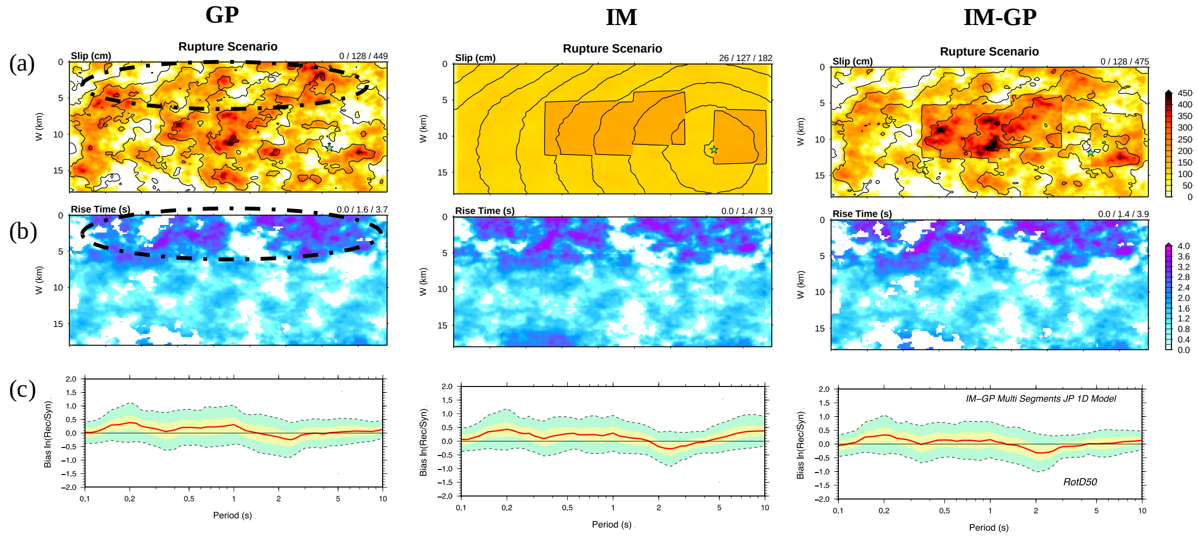


FIG. 6. Broad band simulation results of the Kumamoto earthquake using three different rupture models GP, IM, and IM-GP from left to right. (a) Kinematic slip and (b) total rise time spatial distributions generated with the three models. (c) RotD50 acceleration response spectra bias between recorded and simulated data corresponding to the three models.

5. Conclusions and Future Work

To improve understanding of uncertainties in ground motion evaluation using the fault rupture modeling method, a multi-year research project commissioned by S/NRA/R is under way. A total of 12 continental earthquakes have been systematically analyzed in this project since 2014. The interim results show that the new data are consistent with the scaling laws proposed by previous studies. It also suggests that, as far as the short-period ground motions are concerned, the fault rupture modeling method deals well even with sites with a fault distance of less than 1km.

In light of the lessons learned from the disastrous Kumamoto earthquake, an investigation study starting in 2017 is under way, which integrates geological and geophysical investigations for improving the prediction of fault size. Moreover, a multi-year study on ground motion evaluation for subduction zone earthquakes is also under way. The 2017 research project was commissioned to the Ohsaki Research Institute and the preliminary results are to be reported in this workshop [29].

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