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Tsunami inundation variability from stochastic rupture scenarios: Application to multiple inversions of the 2011 Tohoku, Japan earthquake

Nobuhito Mori[a,*], P. Martin Mai[b], Katsuichiro Goda[c], Tomohiro Yasuda[d]

[a] Disaster Prevention Research Institute, Kyoto University, Japan
[b] Earth Science & Engineering, King Abdullah University of Science & Technology, Saudi Arabia
[c] Civil Engineering, University of Bristol, United Kingdom
[d] Environmental and Urban Engineering, Kansai University, Japan

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ABSTRACT

We develop a framework for assessing the sensitivity and variability of tsunami inundation characteristics for stochastic physics-based scenarios of mega-thrust subduction earthquakes. The method is applied to the 2011 Tohoku, Japan earthquake, and tested against observed inundation maps at several locations along the Tohoku coast, using 11 different, previously published, rupture models for this devastating tsunamgenic earthquake. The earthquake rupture models differ in fault dimension (length and width), geometry (dip, strike and top-edge depth), as well as asperity characteristics (slip heterogeneity on the fault plane). The resulting source variability allows exploring a wide range of tsunami scenarios for an M_w9 mega-thrust subduction earthquake in the Tohoku region to conduct thorough sensitivity analyses and to quantify the inundation variability. The numerical results indicate a strong influence of the reference source models on inundation variability, and demonstrate significant sensitivity of inundation to the details of the rupture realization. Therefore, relying on a single particular earthquake rupture model as a representative case when varying earthquake source characteristics may lead to under-representation of the variability of potential scenarios. Moreover, the proposed framework facilitates the rigorous development of critical scenarios for tsunami hazard and risk assessments, which are particularly useful for tsunami hazard mapping and disaster preparedness planning.

1. Introduction

The current state-of-practice for tsunami hazard mapping for coastal communities mainly considers tsunami hazard parameters (e.g. inundation depths and arrival times of major tsunami waves) that correspond to a single or at most a few scenarios on a selected fault. This approach lacks comprehensive information on the uncertainty of these hazard predictions. Consequently, the range of inundated areas and required structural design criteria cannot be adequately quantified, which in turn hampers the risk communications between tsunami analysts and local stakeholders. Therefore, users of scenario-based tsunami hazard maps may not be able to appreciate the potential risks (and their uncertainties) under different conditions. For instance, during the 2011 Tohoku, Japan tsunami, more than 65% of all fatalities in Kamaishi, Iwate Prefecture were caused outside the regions marked as major inundation zones in public tsunami hazard maps identified prior to 2005. The actual 2011 tsunami was beyond any historical events/scenarios considered for preparing the 2005 hazard map along the Sanriku and Sendai coasts. Clearly, a set of tsunami inundation hazard maps for coastal communities, corresponding to different tsunami scenarios and their consequences, is critically important for adequate tsunami hazard preparedness and evacuation planning. Using probabilistic hazard maps helps to account for the main sources of uncertainty related to the tsunami characteristics, and promotes an informed decision-making for tsunami risk reduction by quantifying and understanding the consequences of different conditions and by communicating the uncertainty of hazard predictions (Pang, 2008).

One of the major challenges for tsunami impact assessment is to predict the earthquake source characteristics of future tsunamigenic events (e.g. location, magnitude, and slip distribution), and to then quantify the uncertainty associated with the variability in earthquake rupture and wave propagation/inundation processes (e.g. Burbidge

* Corresponding author.
E-mail address: mori@oceanwave.jp (N. Mori).

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Table 1
Summary of the 11 slip models.

Model ID and reference	Seismic moment (Nm)	Length (km)	Width (km)	Top-edge depth (km)	Strike, dip, rake (°)	Sub-fault number[a]	Sub-fault size[a] (km)	Data type
1: Fujii et al. (2011)	3.8×10^{22}	500	200	0.0	[193, 14, 81]	10 × 4	50 × 50	Tsunami
2: Satake et al. (2013)	4.2×10^{22}	550	200	0.0	[193, 8–16, 81]	11 × 5	50 × 50/25	Tsunami
3: Shao et al. (2011) [Ver1]	5.6×10^{22}	500	200	4.9	[198, 10, *Var*[b]]	20 × 10	25 × 20	Teleseismic
4: Shao et al. (2011) [Ver2]	5.8×10^{22}	475	200	7.4	[198, 10, *Var*]	19 × 10	25 × 20	Teleseismic
5: Shao et al. (2011) [Ver3]	5.8×10^{22}	475	200	7.4	[198, 10, *Var*]	19 × 10	25 × 20	Teleseismic
6: Yamazaki et al. (2011)	3.2×10^{22}	340	200	3.8	[192, 12, *Var*]	17 × 10	20 × 20	Teleseismic & tsunami
7: Ammon et al. (2011)	3.6×10^{22}	600	210	1.0	[202, 12, 85]	40 × 14	15 × 15	Teleseismic & geodetic
8: Gusman et al. (2012)	5.1×10^{22}	450	200	1.0	[202, 5–20, *Var*]	9 × 5	50 × 40	Tsunami & geodetic
9: Hayes (2011)	4.9×10^{22}	625	260	5.8	[194, 10, *Var*]	25 × 13	25 × 20	Teleseismic
10: Iinuma et al. (2011)	4.0×10^{22}	600	240	1.1	[*Var*, *Var*, *Var*]	60 × 24	10 × 10	Geodetic
11: Iinuma et al. (2012)	4.0×10^{22}	620	260	1.0	[*Var*, *Var*, *Var*]	62 × 26	10 × 10	Geodetic

[a] The first entry is for the along-strike direction, while the second entry is for the down-dip direction.
[b] *Var* represents that the parameter is variable.

et al., 2015). In particular, tsunami propagation and inland inundation characteristics are greatly influenced by complex and nonlinear interaction of earthquake source properties and changes in bathymetry and land elevation (Geist, 2002; McCloskey et al., 2008; Løvholt et al., 2012; Goda et al., 2014). Probabilistic tsunami hazard analysis (Geist and Parsons, 2006; Thio et al., 2007; Gonzalez et al., 2009; Horspool et al., 2014; Fukutani et al., 2015; Mueller et al., 2015; Park and Cox, 2016), is a viable approach to identify tsunami source regions and corresponding scenarios that have major impact to a site of interest. Recently, the American Society of Civil Engineers (ASCE) has announced the new chapter 6 (6.7 *Inundation Depth and Flow Velocity Based on Site-Specific Probabilistic Tsunami Hazard Analysis*) to introduce design requirements for tsunami loads and effects (Chock, 2016) that can be defined through probabilistic tsunami hazard analysis. Therefore, the role of probabilistic tsunami hazard analysis becomes more important in both scientific and engineering fields. When developing critical design scenarios at a specific site, several experts are involved, each with different backgrounds and scientific views, leading to very diverse opinions on potential source characteristics. Such expert judgements rarely result in a consensus model, but rather generate a set of disparate scenarios that need to be weighted in a logic-tree approach (e.g. Fukutani et al., 2015).

Recent development in probabilistic tsunami hazard assessment facilitates the generation of stochastic earthquake source models based on an inverted slip distribution (Mai and Beroza, 2002; Goda et al., 2014, 2015a; Mori et al., 2017). These source models represent possible rupture scenarios having different earthquake slip and fault geometry. Because they are generated semi-automatically within a range of plausible, geophysically constrained parameter choices, they do not require expert judgment. The stochastic method is based on a wave-number domain analysis of slip heterogeneity of inverted slip models, and implements a spectral random-phase approach to generate fault-displacement fields that capture realistic earthquake slip characteristics (i.e. distribution of high slip regions over the fault plane). This procedure allows generating an arbitrary number of synthetic slip models for a range of fault geometries and other source characteristics (e.g. length and width of fault, spectral shape of slip, and ratio of maximum and mean). For example, Goda et al. (2014, 2015a) developed a stochastic earthquake source generation approach for tsunami impact assessment based on an observed rupture model, while Goda et al. (2015b) have extended it to probabilistic tsunami damage assessment. However, their method used a single inverted source model and did not consider the uncertainty in source parameter estimation, as for instance documented in the variations of macroscopic source characteristics of published earthquake rupture models (e.g. Mai and Thingbaijam, 2014). Obviously, it is imperative to consider multiple inversion models to adequately evaluate the tsunami inundation and run-up as well as their variability (MacInnes et al., 2013; Goda et al., 2014, 2015a).

The procedure of stochastic tsunami assessment is useful for assessing the sensitivity and variability of tsunami hazard parameters by propagating the uncertainty associated with tsunami sources from off-shore source regions to inland coastal regions by computing the complete nonlinear fluid-dynamic response of the tsunami. By conducting Monte-Carlo type tsunami simulations based on numerous source models, stochastic inundation depth maps can be generated and then analyzed. Such a stochastic approach for tsunami scenario generation can be easily incorporated into probabilistic tsunami hazard analysis. However, stochastic tsunami assessment strongly depends on observations or historical events to make scenarios or synthetic slips. Therefore, it is important to discuss influence of basic observations or historical events on outcomes (e.g. inundation mapping).

This study investigates the sensitivity and variability of the spatial extent and depth of tsunami inundation considering variations in fault geometry and slip distribution using stochastic rupture models. The stochastic earthquake source realizations are calibrated using multiple results of source inversion. The investigation focuses on the 2011 Tohoku event, because numerous tsunami, seismic, and geodetic observations are available to validate the outcome of the tsunami hazard assessment. Recognizing that different inversion models may reflect different aspects of the earthquake rupture processes, a set of earthquake rupture models (developed by different researchers using different methods and data) can be adopted to characterize parts of the epistemic uncertainty related to source modeling. Although there are many inverted slip models, e.g. a comprehensive summary of estimated static stress drops for the 2011 Tohoku earthquake by Brown et al. (2015), we consider 11 inverted models (Ammon et al., 2011; Fujii et al., 2011; Hayes, 2011; Iinuma et al., 2011, 2012; Shao et al., 2011; Yamazaki et al., 2011; Gusman et al., 2012; Satake et al., 2013) for defining the parameterization for the stochastic earthquake slip distributions. The adopted inversion models have different fault dimensions as well as asperity characteristics. Therefore, a wide range of admissible tsunami scenarios for an M_w9 mega-thrust subduction earthquake in the Tohoku region can be explored, facilitating a detailed sensitivity and variability analysis. For each model, source variations with stochastic slip realizations are synthesized (50 cases per model; thus in total, 550 cases for the 11 inversion models). Note that the stochastic source models generated in this study are intended to cover a wide range of possible earthquake scenarios that may be applicable to probabilistic tsunami hazard mapping. Because the stochastic source models are parameterized by spectral characteristics of a given source model, we examine how different reference inversion models change probabilistic tsunami height and inundation through the stochastic source modeling. Moreover, our investigations produce high-resolution tsunami hazard information with 50-m grid resolution (compared to 450-m grid resolution in Goda et al., (2014)). Tsunami hazard parameters considered are (i) the spatial inundation depth and (ii) the inundated area where depth exceeds certain thresholds. We then quantify the variations of these tsunami hazard estimates due to