

Coupled Simulation of Ground Shaking and Tsunami for Mega-thrust Subduction Earthquakes

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ABSTRACT: A novel framework for concurrently simulating strong motions and tsunami waves is developed. It explicitly considers the dependency of both hazard processes on common source characteristics. The earthquake source properties are modeled stochastically, incorporating various sources of uncertainties. The developed computational procedure is applied to the M_w 9 2011 Tohoku, Japan earthquake. Numerical examples of the coupled simulations of strong motion and tsunami highlight the major impact of source characteristics on strong motion and tsunami hazard parameters. The investigations also provide valuable insights in understanding the spatial impact of cascading earthquake hazards. Such an advanced numerical tool is necessary for assessing the performance of buildings and coastal infrastructure that are subjected to cascading hazards triggered by large subduction earthquakes.

1. INTRODUCTION

The rupture process of mega-thrust subduction earthquakes is a complex phenomenon, governed by pre-rupture stress conditions, geometrical settings, and frictional properties of a fault that are largely unknown. Earthquake source inversions image the space-time evolution of the rupture by matching key features of synthetic data in comparison with various observations (strong motion, teleseismic, geodetic, tsunami; Yokota et al. 2011). A method for stochastic earthquake slip, which is based on the spectral representation of slip heterogeneity and spectral synthesis (Mai and Beroza 2002), provides a powerful means to generate random fields that have realistic spatial slip distributions. Moreover, strong motion generation areas (SMGAs) within the fault, which may be located at different places from asperities (i.e. concentrated large slip patches), have significant influence on strong

motion simulations (Kurahashi and Irikura 2013). Consideration of uncertain common source characteristics for ground shaking and tsunami facilitates the modeling of cascading earthquake-related hazards, and is thus essential for probabilistic assessment of compounding risks due to mega-thrust subduction earthquakes.

This study carries out coupled simulation of ground shaking and tsunami using stochastically generated earthquake source models. It is focused upon the M_w 9 2011 Tohoku, Japan earthquake, for which various geophysical data and shaking/tsunami survey/damage data are available for validation. The framework for the coupled simulation considers uncertainties associated with the rupture process explicitly. The ground motion time-histories are simulated using the multiple-event stochastic finite-fault (SFF) method (Ghofrani et al. 2013), which takes into account multiple local rupture processes in

SMGAs. For tsunami simulation, multiple realizations of wave height profiles due to stochastic slip distributions are generated by evaluating nonlinear shallow water equations with run-up (Goda et al. 2014). The novelty of this research is consideration of common physical rupture processes for strong motion and tsunami simulations, facilitating the assessment of the dependency between shaking and tsunami hazard parameters. In addition, the developed method can be used to investigate the sensitivity and variability of the hazard parameters to uncertain features of asperities and SMGAs. The investigations will provide valuable insights in understanding the spatial impact of cascading earthquake hazards. Such an advanced numerical tool is necessary for assessing the performance of buildings and coastal infrastructure that are subjected to cascading hazards due to large subduction earthquakes.

2. FRAMEWORK FOR COUPLED SIMULATION OF STRONG MOTION AND TSUNAMI

2.1. Computational framework

A novel framework for concurrently simulating ground motions and tsunami waves is developed by considering the dependency of the two hazard processes on source characteristics explicitly. The methodology is illustrated in Figure 1.

Key source parameters that affect simulated ground motion time-histories and tsunami waves for mega-thrust subduction earthquakes can be categorized into two groups: parameters for the background fault plane and parameters for the SMGAs. The size, geometry, location, moment magnitude, stress parameter, and slip distribution of a fault plane are common parameters for both, and can be determined using observed data. The macroscopic parameters (e.g. seismic moment, fault plane area, and average stress parameter) are determined based on information specific to a

given scenario. The number and locations of the SMGAs within a background fault plane can be selected based on the past regional seismicity as well as seismotectonic features. Using empirical scaling relationships for more detailed parameters, moment magnitudes and stress parameters of the SMGAs can be determined. Because the seismic moment, stress parameter, and slip are physically related (Stein and Wyssession 2003), it is desirable to have a consistent source representation of the background fault plane and SMGAs.

Inversion studies for the 2011 Tohoku earthquake and tsunami indicate that source models based on low-frequency data differ significantly from those based on high-frequency data (e.g. teleseismic/geodetic/tsunami inversion versus strong motion inversion; Yokota et al. 2011; Kurahashi and Irikura 2013). Typically, results based on low-frequency data place large slip patches near the epicenter and along the Japan Trench at shallow depths. On the other hand, results based on high-frequency data suggest that multiple localized areas, which radiate intense high-frequency seismic energy, are required at relatively deep locations to explain multiple-shock features of the observed accelerograms at recording stations.

An unresolved issue is that a unified theory which explains frequency-dependent source rupture processes has not been fully developed for future predictions of strong motion and tsunami due to large subduction earthquakes. To put it differently, asperities (where large slip occurs) and SMGAs (where large slip velocity or high stress drop occurs) can differ. Currently, there is only a weak linkage between the overall background slip process and SMGAs. Examples of such linkages include the seismic moment constraint and the empirical area ratio of the SMGAs to the total fault plane (Irikura and Miyake 2011).

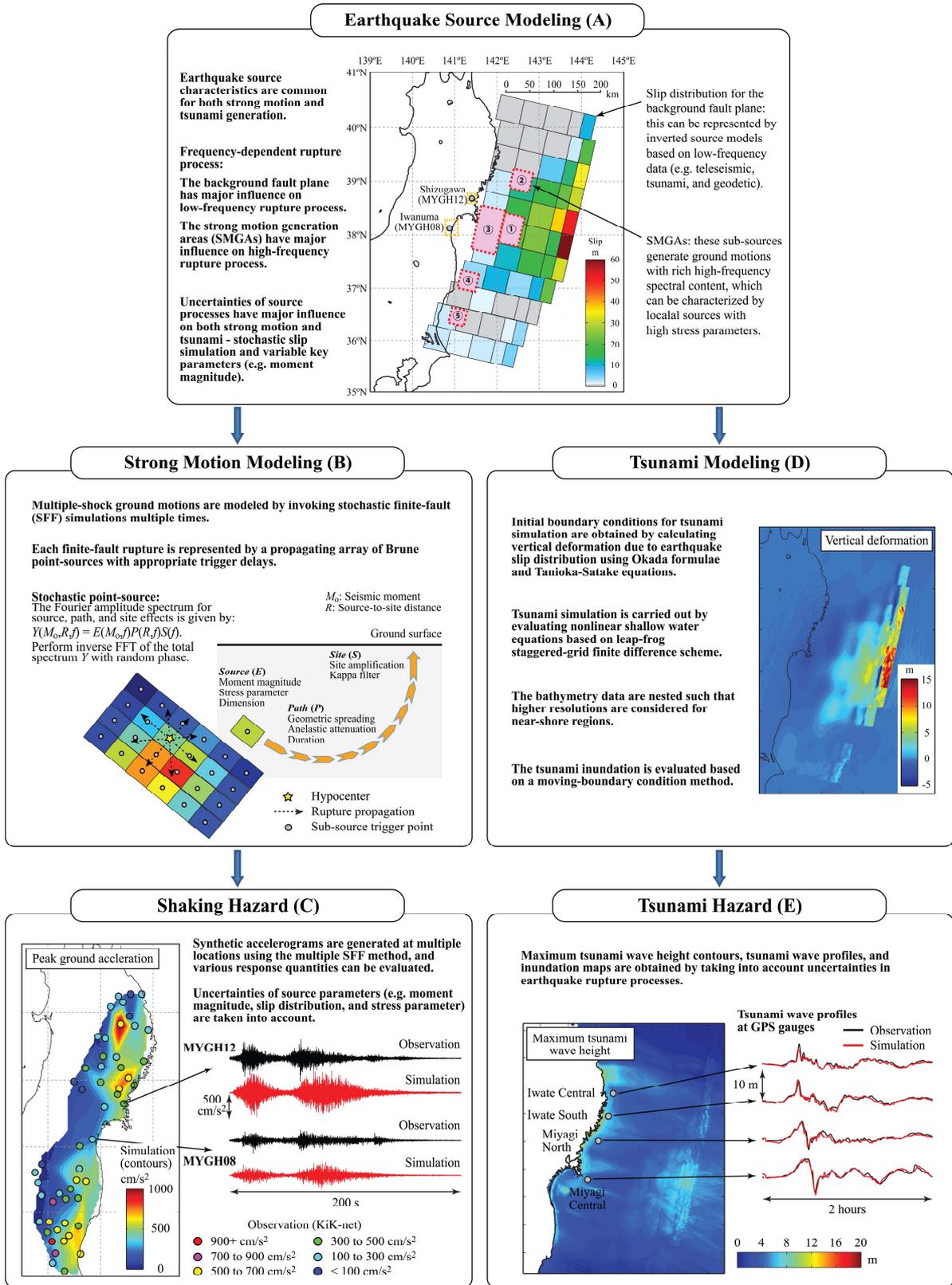


Figure 1: Computational framework for coupled simulation of strong motion and tsunami.

This study adopts the state-of-the-art source modeling approach for mega-thrust subduction earthquakes. The source characteristics of the background fault plane (involving asperities) are represented by inversion-based source models for low-frequency processes, whereas those of the SMGAs are modeled by strong-motion-based source models for high-frequency processes (Kurahashi and Irikura 2013). A graphical representation of the source modeling is shown in Panel A of Figure 1. To account for uncertainties of the background source process, slip distributions are generated using the spectral synthesis method (Goda et al. 2014). This method generates numerous slip distributions that have similar marginal as well as spatial spectral characteristics to inverted source models. As inverted source models differ significantly, multiple source models are considered to account for epistemic uncertainties related to earthquake source modeling. For the SMGAs, key parameters, such as stress parameter and moment magnitude, are varied based on statistical distributions. The interaction between the background fault plane and SMGAs is determined via the seismic moment and area constraints.

Subsequently, strong motion simulations are performed using the multiple-event SFF method (Panel B of Figure 1), which takes into account both background slip distribution and SMGAs. Strong shaking hazards (e.g. contour maps of ground motion intensity measures) can be evaluated by generating numerous realizations of accelerograms at different locations (Panel C of Figure 1). Concurrently, initial tsunami height profiles due to earthquake rupture are computed based on the background slip distributions (Panel D of Figure 1), and tsunami simulations are conducted. Finally, tsunami wave profiles (both off-shore and on-shore) and stochastic tsunami hazard maps can be evaluated for different locations (Panel E of Figure 1). Therefore, the developed tool can be used for simulating coupled hazard processes as well as for assessing their sensitivity to variable source characteristics.

2.2. Strong motion simulation

The SFF method approximates ground motions as a propagating array of Brune point sub-sources, each of which can be modeled as a stochastic point source (Boore 2009). The spectrum of a point source is defined by multiplying source, path, and site spectra in the frequency domain, and inverse fast Fourier transform (FFT) is then applied to a white noise filtered through the modified spectrum to obtain simulated acceleration time-histories (Panel B of Figure 1). The low-frequency spectral level is determined by the moment magnitude of an entire fault plane, whereas the high-frequency spectral content is controlled by the stress parameter of sub-sources. Each sub-source is activated once, with an appropriate delay time based on rupture propagation from a hypocenter to the sub-source.

To model the observed multiple-shock features for the 2011 Tohoku earthquake, Ghofrani et al. (2013) have extended the SFF method to consider multiple events. Specifically, the multiple-event SFF method triggers SFF simulations multiple times for the background fault plane and SMGAs with appropriate rupture delay times. Its key feature is that the complexity and heterogeneity of source characteristics are modeled explicitly by assigning different sets of model parameters to individual rupture segments radiating intense high-frequency energy. The strong motion simulation based on the multiple-event SFF method starts with fault rupture of the background fault plane, and then SMGAs are triggered with time delays to account for realistic rupture propagation within the fault plane. Synthesized time-histories from the background and SMGAs are summed in the time domain. Low-frequency components of the synthesized ground motions are mainly contributed by the background plane, whereas SMGAs have significant influence on high-frequency components.

The multiple-event SFF model for the 2011 Tohoku mainshock is calibrated using real ground motions recorded at the KiK-net stations

(Panel C of Figure 1). To reflect inherent uncertainties in key parameters of the multiple-event SFF model, the background parameters are varied by adopting multiple stochastic slip models and by randomizing the stress parameter (modeled as a lognormal variate with the coefficient of variation of 0.35). For the SMGAs, locations, magnitudes, and stress parameters are treated as random variables by adopting the spatial Gaussian smoothing function, truncated normal distribution, and lognormal distribution, respectively. The representative (mean) parameters are the same as those in Ghofrani et al. (2013). The standard deviation for the spatial smoothing function is set to a quarter of the characteristic fault dimension, the standard deviation of the moment magnitudes is set to 0.2 (truncation at mean plus/minus one standard deviation), and the coefficient of variation for the stress parameters is set to 0.35.

2.3. Tsunami simulation

Tsunami modeling is carried out using a well-tested numerical code (Goto et al. 1997) that is capable of generating off-shore tsunami propagation and inundation profiles by evaluating nonlinear shallow water equations with run-up using a leap-frog staggered-grid finite difference scheme. For simulating the 2011 Tohoku tsunami, information on bathymetry, surface roughness, and coastal defense structures is obtained from the Cabinet Office of the Japanese Government. The computational domains are nested at four resolutions (i.e. 1350-m, 450-m, 150-m, and 50-m domains). Computational cells include those on land, and coastal defense structures are taken into account using overflowing formulae as a sub-grid model.

In this study, multiple stochastic source models (Panel A of Figure 1) are used for

tsunami simulation. The fault rupture is assumed to occur instantaneously. To compute initial water surface elevation for a given earthquake slip model (Panel D of Figure 1), analytical formulae for elastic dislocation by Okada (1985) together with the equation by Tanioka and Satake (1996) are used. The latter is to take into account the effects of horizontal movements of steep seafloor on the vertical water dislocation. Numerical tsunami calculation is performed for duration of 2 hours with an integration time step of 0.5 s.

The tsunami simulation results produce tsunami wave profiles at specific locations (e.g. GPS buoy gauges) as well as maximum tsunami wave height contours (Panel E of Figure 1). At sub-municipal levels, inundation footprints can be evaluated. Furthermore, uncertainties of tsunami inundation and wave heights associated with future scenarios can be assessed by considering stochastic slip distributions.

3. APPLICATION

This section presents an application of the developed computational tool for coupled simulation of strong motion and tsunami. The application is focused upon two locations: Iwanuma in Sendai coastal plain and Shizugawa in Sanriku ria coast. The tsunami inundation footprints are sensitive to topographical features of local terrains. Their locations are indicated in Panel A of Figure 1. The code names of the KiK-net stations in Iwanuma and Shizugawa are: MYGH08 and MYGH12, respectively. The aim of the application is to highlight the capability and utility of the developed tool for the coupled simulation of strong motion and tsunami in assessing the cascading multi-hazards by taking into account uncertainties.

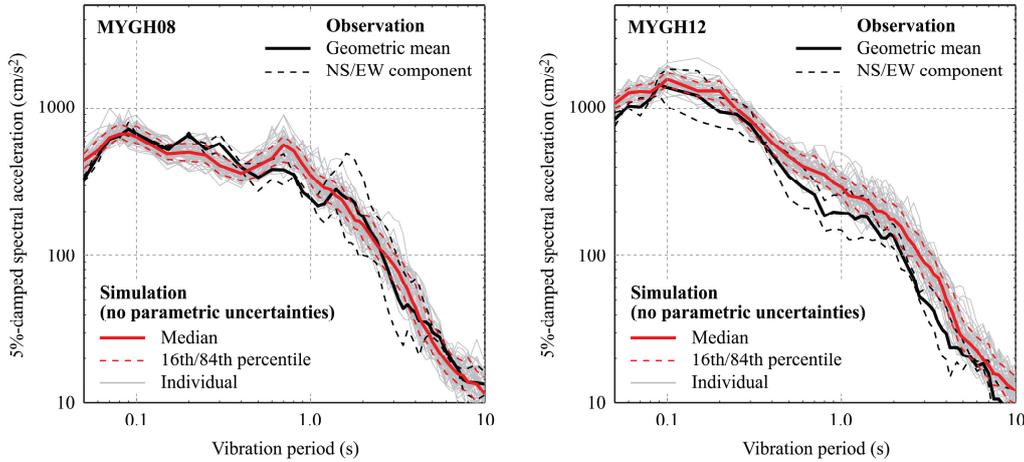


Figure 2: Comparison of observed and simulated response spectra at MYGH08 (Iwanuma) and MYGH12 (Shizugawa). Uncertainties of the source parameters are not taken into account.

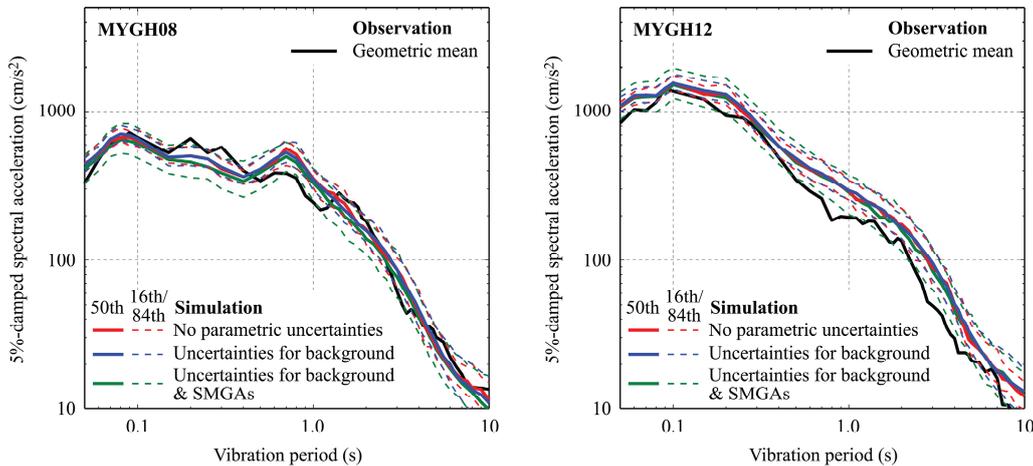


Figure 3: Comparison of observed and simulated response spectra at MYGH08 (Iwanuma) and MYGH12 (Shizugawa) without and with uncertainties of the source parameters.

3.1. Strong motion in Iwanuma and Shizugawa

The reference source model by Ghofrani et al. (2013) considers a uniform slip distribution for the background fault plane and a moment magnitude of 8.92. The moment magnitude based on the total seismic moments for five SMGAs is 8.54. The stress parameter of the background fault plane is 3.5 MPa, whereas those for the SMGAs range from 16 to 41 MPa. The locations of the SMGAs are shown in Panel A of Figure 1. Using the reference model, 50 realizations of accelerograms at MYGH08 and MYGH12 are generated. A comparison of the

simulated and observed time-history data at these locations is presented in Panel C of Figure 1. The response spectra of the simulated accelerograms at MYGH08 and MYGH12 (thin grey lines) as well as their statistics (i.e. median [50th] and 16th/84th percentiles; solid/dashed red lines) are compared in Figure 2 with the response spectra of the observed records (solid/dashed black lines). The variability of the synthesized results is due to different realizations of white noises in SFF simulations. The results indicate that the simulated records at the two sites can capture key temporal as well as spectral features of the observed records.

Next, the effects of incorporating uncertainties of the source parameters on the simulated ground motions and their response spectra are evaluated. In the strong motion simulation module of the developed framework, uncertainties of various parameters (e.g. moment magnitude, stress parameter, location and size) can be included. Two additional sets of strong motion simulations are carried out. Case 1 considers uncertainties related to the background fault plane. In particular, the background fault planes and slip distributions are obtained from stochastic slip models based on Satake et al. (2013), noting that this set-up leads to variable moment magnitudes, fault geometry, and slip distributions (i.e. asperities) of the background

fault plane. The stress parameter of the background fault plane is also varied. Case 2 takes into account variability of the SMGA parameters, in addition to the variable parameters for the background fault plane as in Case 1. Specifically, moment magnitudes and stress parameters of the five SMGAs are varied randomly according to the assumed probability distributions (i.e. truncated normal and lognormal distributions, respectively). Moreover, locations of the centers of the SMGA fault planes are varied using the spatial Gaussian smoothing function. Figure 3 compares the statistics of the response spectra of the simulated ground motion records for the base case, Case 1, and Case 2 at MYGH08 and MYGH12. The geometric mean

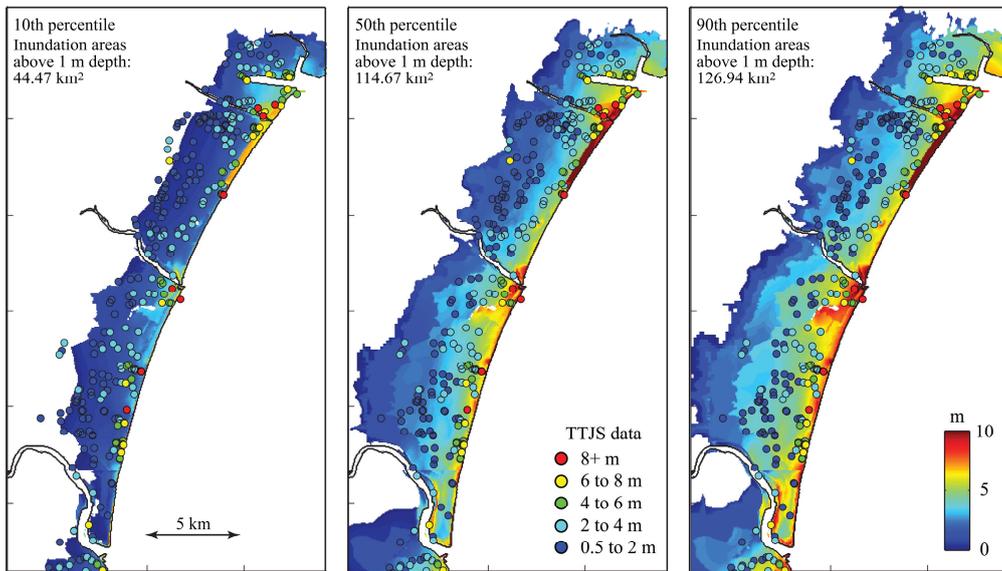


Figure 4: Stochastic inundation depth contour maps for Iwanuma.

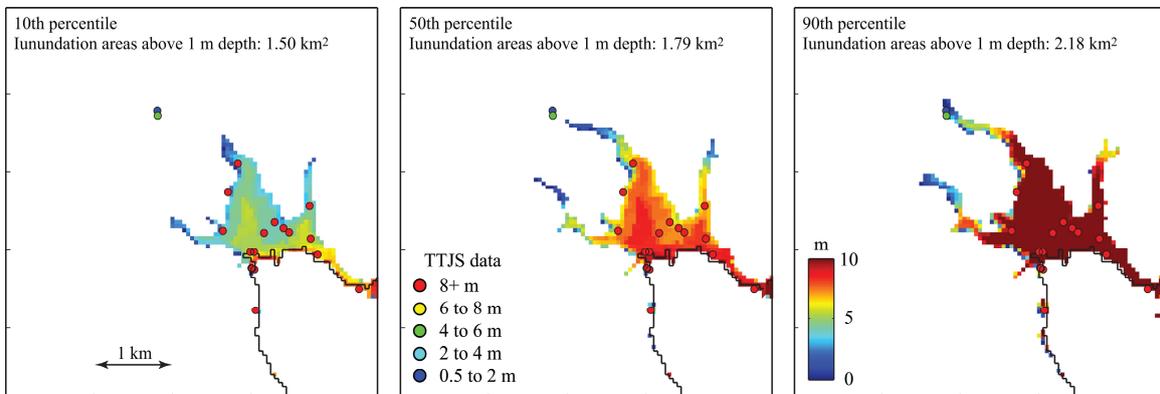


Figure 5: Stochastic inundation depth contour maps for Shizugawa.

response spectrum of the observed records is also included in the figure. The results indicate that the median curves for the three cases are not affected by the inclusion of parametric uncertainties. The consideration of uncertainties for the background fault plane (red versus blue) results in increased variability of the simulation results at long vibration periods (i.e. low-frequency). This is mainly due to the variations of the moment magnitude and slip distribution. On the other hand, the inclusion of uncertainties related to the SMGAs leads to the increased variability of the response spectra at short vibration periods (i.e. high-frequency). The results shown in Figure 3 help understand the influential model components on different characteristics of strong motions and appreciate the inherent impact of underlying uncertainties associated with predictions.

3.2. Tsunami inundation in Iwanuma and Shizugawa

The spatial and depth extent of tsunami inundation for the M_w 9-class mega-thrust subduction earthquake in the Tohoku region is evaluated using the developed tool. For the assessment, stochastic slip distributions that are based on the tsunami inversion source model by Satake et al. (2013) are employed. The variable slip distributions change the locations as well as concentrations of asperities within the fault plane. This has a major influence on the simulated tsunami inundation footprints at regional as well as local levels. Figures 4 and 5 show the simulated inundation depth contours for Iwanuma and Shizugawa, respectively, based on the slip models that are associated with 10th percentile, median, and 90th percentile with regards to inundation areas above 1 m depth. The contours visualize the variability of the inundation footprints due to the slip variations (i.e. stochastic inundation maps). To compare the simulated tsunami inundation footprints with the observed tsunami run-up survey results, an extensive dataset gathered and compiled by the Tohoku Tsunami Joint Survey (TTJS) team (Mori et al. 2011) are used. To facilitate the

visual inspection of the simulated inundation maps and the survey results, similar color schemes are adopted.

The results for Iwanuma (Figure 4) suggests that both spatial and depth extents of inundation are greatly affected by uncertain source parameters (particularly, slip distribution). In terms of inundation areas above 1 m depth, a factor of 3 differences (or more) is possible due to the variable slip distributions (for similar M_w 9-class earthquakes). The observed tsunami inundation (i.e. TTJS data) agrees well with the median scenario, indicating that the tsunami inundation in Sendai coastal plains experienced during the 2011 Tohoku tsunami is not the worst case scenario, and potentially, more extreme tsunami inundation can happen.

The results for Shizugawa (Figure 5) indicate that the spatial extent of inundation is not affected remarkably by the variations in slip distributions, whereas the depth extent of inundation increases significantly with the percentile level. This is because for most of the considered stochastic scenarios, tsunami waves reach topographical boundaries where elevations start to become steeper. For the 90th percentile scenario, most of the low-lying areas of Shizugawa experience very high inundation depths (more than 10 m). In fact, the observed inundation during the 2011 Tohoku event is similar to the 90th percentile inundation depth contour map. Based on this, the observed 2011 tsunami may be considered as one of the worst scenarios for this town.

Use of stochastic slip distributions facilitates the uncertainty quantification of potential tsunami hazards. These are particularly effective in visualizing and communicating uncertainties associated with the tsunami input boundary conditions. In hazard mapping and tsunami evacuation planning, consideration of variable slip distributions should be an imperative part of tsunami hazard assessments.

4. CONCLUSIONS

The newly developed computational framework for coupled simulation of strong motion and

tsunami due to mega-thrust subduction earthquakes has great potential to address key challenges related to cascading multi-hazards and risks to buildings and infrastructure in the coastal region. The methodology is innovative in several aspects: (i) common physical characteristics of earthquake rupture are explicitly modeled and cascading hazard processes are simulated following the trigger phenomenon; (2) uncertainties of source characteristics are taken into account; and (3) both spatial and temporal hazard processes can be evaluated. The framework provides new opportunities to assess the dependency between strong motion and tsunami predictions due to common uncertain earthquake slip at different spatial as well as temporal scales. These have important implications on risk assessment and mitigation methods for coastal structures subjected to cascading multi-hazards.

5. ACKNOWLEDGEMENTS

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