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Validating slip distribution models of the 2011 Tohoku earthquake with diffracted tsunami and uplift-induced sea waves in the back-arc region

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SUMMARY

We investigate slip-distribution models of the 2011 Tohoku earthquake, with a particular focus on diffracted tsunamis and uplift-induced waves along the back-arc region of the Japanese Island Arc. The 2011 Tohoku earthquake produced a large amplitude tsunami that diffracted around Kyushu Island before reaching Korea. At the same time, this earthquake co-seismically induced short-period small-amplitude sea waves in the East Sea. We performed tsunami simulations using seven fault models of the Tohoku earthquake to examine whether the models can accurately reproduce the observed waveforms in the open sea of the western Pacific Ocean, the South Sea of Korea, and the coast of the East Sea. For each fault model, we investigate tsunami features due to geomorphological characteristics of the Korean Peninsula in the Korea offshore. To determine which slip distribution model shows a good performance in the tsunami simulations, we set three criteria; the delay time between observations and synthetic waveforms, the normalized mean residual, and the normalized RMS misfit. Depending on the study region, all models show varying degrees of accuracy. The fault dimensions and the amount of slip have a larger effect on the RMS misfit then the slip distribution patterns of the fault models for observations along the Korean coast and the western coast of Japan.

**Keywords:** Japan; Tsunamis; Earthquake dynamics; Numerical Modelling; Wave scattering and diffraction
1. Introduction

Large subduction zone earthquakes like the 2011 Tohoku earthquake have heterogeneous slip distribution patterns (e.g., Kikuchi & Fukao 1987; Thatcher 1990). Many slip distribution models have been presented to characterize the source of the 2011 Tohoku earthquake using a variety of observation data, such as teleseismic records (Hayes 2011; Lay et al. 2011; Polet & Thio 2011), strong ground motion (Suzuki et al. 2011), GPS (global positioning system) data (Iinuma et al. 2011), and tsunami records (Tajima et al. 2013; Satake et al. 2013). Some studies have conducted tsunami simulations to confirm the accuracy of their earthquake source models (Lee et al. 2016; Petukhin et al. 2017). Moreover, some studies compared tsunami simulation results using variant seismic and tsunami source models of the Tohoku earthquake (Ulutas 2013; Breanyn et al. 2013). It is common to compare calculated results with tsunami observations in order to confirm the validity of the numerical source models in the process of modeling a large earthquake source or a numerical tsunami propagation. If a model is not realistic or not well constructed, it cannot reproduce observation-like results.

Since Korea began instrumental sea-wave recording (i.e., tidal gauges) in the 1900s, five tsunamis from Japan have reached Korean coasts. They are the 1940 Shakotan-oki tsunami, the 1964 Niigata tsunami, the 1983 Akita-oki tsunami, the 1993 southwest-of-Hokkaido tsunami, and the 2011 Tohoku-oki tsunami (Fig. 1). The first four tsunamis occurred along the western coast of Tohoku and Hokkaido in Japan. And they directly propagated towards the Korean coast from the source regions across East Sea (Sea of Japan). However, the 2011 Tohoku earthquake generated a large tsunami in the western Pacific Ocean, and the primary direction of tsunamis turned around Kyushu Island before reaching the southern coast of the Korean Peninsula. This diffracted wave was considerably attenuated during its propagation from the source region towards Korea and was perturbed by Kyushu Island. As in the case of the 2004 Sumatra tsunami, the diffracted tsunamis caused as much damage as tsunamis that directly hit the land (Poisson et al. 2009). Thus, there is a need to understand how sea floor topography can affect different aspects of tsunami propagation as well as how the morphological features of ruptured faults, such as the location, extent, and geometry, affect the characteristics of diffracted waves.

The East Sea contains three major deep (> 1 km) basins, the Ulleung, Yamato, and Japan basins, all of which were formed under an extensional tectonic regime. Separation of the Japanese
Island Arc from the continent resulted in the creation of the East Sea, an almost completely isolated
sea basin, which has several straits, such as those connecting it to the East China Sea in the south-west
and the Okhotsk Sea in the north-east. When the Tohoku earthquake generated a tsunami off the coast
of Japan, the tsunami entered into the East Sea through the Tsugaru Strait between Honshu and
Hokkaido Island; this wave was captured by several tide gauges along the coast of the East Sea
(Shevchenko et al. 2014; Murotani et al. 2015; Lee et al. 2016). When the tsunami diffracted Kyushu
Island, the wave was also able to penetrate into the East Sea through the Korea Strait, which is located
between the Korean Peninsula and Kyushu Island. However, the diffracted tsunami was barely
observable at tide gauges along the eastern coast of Korea. Meanwhile, immediately after the Tohoku
earthquake, small sea waves with short-period oscillations appeared in coastal area throughout the
East Sea. These waves were recorded at several tide gauges along the eastern coast of Korea as well
as the western coast of Japan. Such short-period components of a sea wave are unusual characteristics
for a tsunami.

The characteristics of the wave diffraction and oscillation in a region of geometric shadow of
a tsunami are controlled by source locations as well as any potential obstacles of primary tsunami
propagations. In the case of tsunami generation, an earthquake source model described by several
parameters such as rupture dimension, fault geometry, and slip distribution can be a variable, while
the location and geometry of the obstacle are the given conditions. Therefore, the diffracted tsunamis
and short-period oscillations in the Korea offshore may be useful observables to evaluate the
characteristics of various earthquake source models in tsunami observations. Some studies have
already demonstrated the precise reproduction of tsunamis by earthquake models performing tsunami
simulations with various earthquake slip distribution models (MacInnes et al. 2013; Ulutas 2013);
however, they only compared synthetic results with the primary propagation of tsunami with the
observations close to the earthquake source region. This study compares seven different slip
distribution models of the 2011 Tohoku earthquake by applying one of the common numerical
tsunami models, the nonlinear shallow water equation (e.g., Satake 1995), to investigate how
accurately the slip distribution models reproduce diffracted tsunamis and short-period waves in the
southern coasts of Korea and the coast of the East Sea. We also explore tsunami aspects due to
geomorphological characteristic of the Korean Peninsula in the offshore of Korea for each fault
models.
2.Methods

2.1 Slip models and initial conditions

We applied tsunami simulations to seven slip distribution models of the 2011 Tohoku earthquake in order to compare numerical waveforms with tsunami observations. The models were selected based on their inversion methods (Table 1) and slip distribution patterns (Fig. 2). Models M1 and M2 were derived from inversion of tsunami waveforms (Fujii et al. 2011; Satake et al. 2013). Models M3, M4, M5, and M6 were derived from inversions using teleseismic P, SH, and long period surface waves (Shao et al. 2011; Hayes 2011). Model M7 was inferred from teleseismic P waves, short-arc Rayleigh waves, and high-rate GPS data (Ammon et al. 2011).

Models M1 and M2 were derived from tsunami waveforms recorded at GPS tide gauges, coastal tide gauges, and deep-ocean bottom-pressure gauges (Fujii et al. 2011; Satake et al. 2013). In the inversions for both models, the Japan Meteorological Agency (JMA) hypocenter (38.103°N and 142.861°E, depth = 24 km) was used. The fault area for M1 was divided into 10 x 4 sub-faults that have dimension of 50 km by 50 km each. The directional parameters of each sub-fault (strike 193°, rake 81°, and dip 14°) were taken from the United States Geological Survey (USGS) W-phase moment tensor solution. M2 is an advanced version of M1, with consideration of additional tsunami waveforms and temporal changes of slip. It consists of 11 x 5 sub-faults measuring 50 km by 50 km each, but two columns of sub-faults near the trench have a subfault width of 25 km wide. This model has the same strike and rake as M1 whereas the dip varies depending on the depth of the sub-faults. The maximum slip of M1 and M2 is approximately 40 m and 70 m, respectively, at the shallowest part of the source region.

Models M3, M4, and M5 were suggested by Shao et al. (2011) and created based on the finite fault inversion method of Ji et al. (2002). The fault plane was determined by multiple double-couple analysis using two different seismic datasets consisting of teleseismic body waves and long period surface wave observations, resulting in a strike of 199°, a dip of 10°, and a rake of 92°. M3 was inferred using the USGS PDE hypocenter (38.322° N and 142.369° E, depth = 24 km). The dimension of the fault plane is 500 km-by-200 km and it consists of 200 sub-faults (25 km-by-20 km). The estimated maximum slip is approximately 40 m. In model M4, the top side of the fault plane is placed

Table 1 here

Fig. 2 here
nearest the trench axis. JMA’s hypocenter was used but the depth was modified from 24 km to 23 km in the inversion. The number of sub-faults was 10 x 19 but the size of each sub-fault was the same as that of M3; thus, the whole fault plane was smaller than M3. Its large slip area was extended to the down-dip direction to be distributed near the source point and the peak slip was approximately 56 m. Model M5 was determined using more station data and the weight of the surface waves was doubled. The number and size of sub-faults were the same as that of M4. The dominant slip area was larger than those in other models and extended along the trench axis as well as in the down-dip direction.

For model M6, the authors used the modified strike (195°) and dip (10°) of the early W-phase solution that better fits the Slab 1.0 global subduction interface model to the inversion (Hayes 2011). This model was derived from an inversion using the USGS source location (142.37°E, 38.32°N) and a depth of 30 km, which is approximately 6 km deeper than the early USGS depth (approximately 24 km) and more adjacent to the slab interface depth. The dimension of this model was 625 km (along strike) by 260 km (along dip), divided into 325 segments of 25 km by 20 km. This model had the largest fault plane among the seven source models. Even if the same inversion method was used for M3 to M6, we would expect different results in the tsunami simulation due to the different slip distribution generated by various the moment tensor solutions, hypocenter, and datasets.

Model M7 was inferred using teleseismic P waves, short-arc Rayleigh waves, and three-component high-rate GPS (30 s sampling rate) data. This model was composed of 14 x 40 sub-faults measuring 15 km-by-15 km each, which was the finest size among all seven models. The fault geometry was set to a strike of 202°, a rake of 85°, and a dip of 12° for all sub-faults. The largest slip was distributed near the hypocenter whereas the asperities in the other models were located near the shallowest part of the trench.

For the initial tsunami heights in tsunami simulations, seafloor deformation distribution is calculated using Okada’s formula (Okada 1985). The horizontal movement of seafloor slope is also considered in the calculation (Tanioka & Satake 1996; Fig. 3). Note that most of source models have spatiotemporal rupture history, but we assume seafloor deformation occurs instantaneously.

The result using M1 shows large deformation near the hypocenter and larger uplift at the shallowest part of the fault plane. In most of the models, the largest slip is distributed along the trench axis. Models M1, M4, and M5 exhibit larger subsidence than other models. M6 displays uplift on the northern side of the fault plane and subsidence on the western coast of Honshu, Japan. Values of total
vertical seafloor deformation from the seven models were used as initial sea water amplitudes in the tsunami simulations.

2.2 Numerical simulation

To check if the slip models accurately reproduce the diffracted tsunami waveforms and waves with short period components in the East Sea, we compared synthetic waveforms with observations from tide gauges. For the numerical computation, we set the boundaries of the simulation region to 115°E–160°E and 20°N–50°N, which includes the northwest Pacific Ocean, Japan, and the Korean Peninsula (Fig. 1). We used 30 arc-second bathymetry grid data provided by the General Bathymetric Chart of the Ocean (GEBCO; GEBCO_2014 Grid). Before applying the seven source models for the tsunami simulations, we tested sensitivity of bathymetry grid spacing using 30 arc-second and 15 arc-second data. The test showed that there is inconsiderable discrepancy between two simulation results. This validates the usage of 30 arc-second bathymetry data in our simulations reducing computational load. The nonlinear long-wave equations were solved using the staggered leap-frog finite difference method (e.g., Satake 1995) with a time step of 1 s. We also included inundation calculations by changing the boundary between land and water according to water flow into the land area (e.g., Iwasaki & Mano 1979; Saito et al. 2014).

The 2011 Tohoku tsunami was recorded at various gauges near the Japanese coast, and some waves were also captured by several Korean tide gauges. Many DART buoys were operating in the Pacific Ocean when the Tohoku earthquake generated the tsunami, and thus the tsunami observations of the DART buoys 21401, 21413, 21418, and 21419 are hired for this study to verify if we performed plausible tsunami simulations. In order to see whether the seven slip models reproduce the diffracted tsunami which turned around Kyushu Island and reached the southern coast of Korea, we collected tsunami data from the two stations, Moseulpo and Seogwipo, located along the Jeju coast, and the three stations, Goheung, Tongyeong, and Geomun-do, along the southern Korean coast (Fig. 1). We also added a Japanese tide gauge, Akune, located in Kagoshima on Kyushu Island, which we will refer to as being in “the South Sea of Korea”. Immediately after the Tohoku earthquake, some amplitude changes were observed at tide stations along the northwestern coast of Honshu, Japan (Shevchenko et al. 2014; Murotani et al. 2015), including short-period waves. We obtained tidal records from Wajima, Ogi, and Nezugaseki stations located on the northwest coast of Japan to
investigate if the slip models reproduce the amplitude change that occurred immediately after the origin time. In addition, we obtained tidal data from tide gauges at Sokcho, Mukho, Pohang, and Hupo, located along the eastern coast of Korea to include the features of small waves with short-period oscillations in Korea.

The numerical simulations in this study considers diffracted waves with relatively long path lengths. In this case, the second-order effects such as the linear dispersion (e.g., Saito et al. 2014), crustal loading and seawater density (e.g., Inazu and Saito 2010; Tsai et al. 2013) as well as non-dispersive tsunami (e.g., Satake 1995) can cause delays in tsunami arrivals due to energy loss during distant tsunami propagation. Inazu and Saito (2010) showed that the delay of the distant tsunami propagation is mostly caused by the self-attraction and loading effects rather than seawater-density stratification. Thus, we tested the crustal loading effect only in the nonlinear long-wave equation. Consideration of the crustal loading effect showed slight delay in the tsunami arrivals compared to the results without the effect. Meanwhile both the results showed unnoticeable differences in the root-mean-square (RMS) misfits with the observed tsunami waveforms at tidal gauges along the Korean coast. This means that in that propagation path are common to all the source models, path effects are not be of primary concern in this study.

3. Comparison of observations and simulated waveforms

In order to quantify the performance of the different source models of the 2011 Tohoku earthquake, we investigated the following criteria: the delay time of the first peak (i.e. dominant leading phase), the normalized mean residuals, and the normalized root-mean-square (RMS) misfit. Moreover, we also calculated the mean of normalized mean residuals and mean of normalized RMS misfit of 17 stations. We cross-correlated the first peak of observations and synthetic waveforms at each station to calculate the lag time between two wave-profiles. This lag time is to investigate how precisely the source models predict the arrivals of the first peak and it shows the simulated tsunami
reaches earlier or later than real tsunami.

Normalized mean residual $r_{ij}^{(st)}$ determine whether the simulated tsunami is overestimated or underestimated compared to the observations. When $r_{ij}^{(st)}$ is close to zero, it means that the simulation results approximate the observations. The size of the residuals depends on the amplitudes at each station. Thus, in order to make a fair comparison between all stations, we conducted normalization. $r_{ij}^{(st)}$ between the observed and synthetic waves for the $j^{th}$ station associated with $i^{th}$ fault model is defined as

$$r_{ij}^{(st)} = \frac{1}{\sqrt{K}} \cdot \frac{\sum_{k=1}^{K} (O_k - S_k)}{\sum_{k=1}^{K} (O_k - \bar{O}_\text{mean})^2}, \quad (1)$$

where $O_k$ and $S_k$ are signal values of observed data and synthetics, respectively, at a time point $t_k$ with the total number $K$ of time points. $\bar{O}_\text{mean}$ stands for the mean value of the observed signal.

We further define the mean of the normalized mean residual (simply the mean residual) among stations associated with the $i^{th}$ fault model such as

$$r_i^{(f \text{ model})} = \frac{1}{J} \sum_{j=1}^{J} r_{ij}^{(st)}, \quad (2)$$

where the index $j$ is $j^{th}$ station and $J$ is the total number of stations, 17 in this study. When $r_i^{(f \text{ model})}$ is calculated, we performed bootstrapping for 1000 iterations to estimate uncertainties. The bootstrapping was performed by randomly sampling the original set of values with replacement to obtain a new set of values with 14 and original set is 17. A statistic, such as the mean or RMS is then calculated on this new set. This is repeated 1000 times to allow us to make an estimate of the error in that statistic.
For the normalized RMS misfit of the signals between observation and synthetic, we first define the normalized RMS misfit for $j^{th}$ station associated with $i^{th}$ fault model:

$$\mathcal{R}_{ij}^{(st)} = \sqrt{\frac{\sum_{k=1}^{K} (O_k - S_k)^2}{\sum_{k=1}^{K} (O_k - O_{mean})^2}}.$$  

(3)

The mean of normalized RMS misfit (or simply the mean RMS misfit) of 17 station for the $i^{th}$ Fault model is calculated as below:

$$\mathcal{R}_{i}^{(f_{model})} = \frac{1}{J} \sum_{j=1}^{J} \mathcal{R}_{ij}^{(st)},$$

(4)

This $\mathcal{R}_{i}^{(f_{model})}$ is computed using the bootstrapping with 1000 iterations and a set of 14 stations at each time step.

3.1 The western Pacific

Here, we compare synthetic tsunami results and observations of the western Pacific Ocean. As mentioned in the previous section, DART buoys 21401, 21413, 21418, and 21419 were selected to verify that our tsunami simulations are reasonable. Tidal effects were removed from the observations by applying a high-pass filter with a corner frequency of 0.0347 mHz or a period of approximately 8 h. Fig. 4 show arrival time and maximum amplitude of the synthetic peaks match well with the observations at the DART buoys. DART buoy 21418 is the closest one to the earthquake source region, and we observe large wave heights (~ 1.9 m) and the maximum peak arrives within 30 min of the origin time. Buoys 21401 and 21419 are located to the north of the earthquake epicenter, and observations at those stations show that the tsunami amplitudes decrease due to the spreading tsunami waveforms from the source region. The maximum observed peak at both stations is 0.6 m and 0.5 m, respectively, and the simulation results also show much lower tsunami peaks than those at station 21418. Even though the maximum amplitudes of the simulated results differ slightly from the...
observations depending on the source model, they are typically close to the observations.

The lag times obtained from cross-correlation of the first peak between the observations and synthetic waveforms also indicate it and their time gap is shorter than other areas (Table 2, Fig. 5) which means synthetic tsunami waveforms arrived similar time as real tsunami despite M5 arrived ~3 min earlier than observations.

A time window of 40 min, starting approximately 5 min before the first arrival, was used for the DART buoys to calculate $r_{ij}^{(st)}$ and $R_{ij}^{(st)}$. Fig. 6a shows $r_{ij}^{(st)}$ of the seven models for DART buoy data. Most models predict lower amplitudes than that of tsunamis observations at the DART buoys while $r_{i}^{(f_{model})}$ show that slip models overestimate wave amplitudes, except for model M6. The value for model M6 is slightly tilted towards the positive from zero, which means that model M6 shows the least bias at the DART buoy stations. Even if some models resulted in higher first peak than observed data, the $r_{ij}^{(st)}$ indicate the models underestimated tsunami amplitude. This is because the crest of wave is under estimated than observation e.g. M5 at DART buoy 21413 and $r_{ij}^{(st)}$ tell us average tendency of the prediction during the time window.

Fig. 7a shows $R_{ij}^{(st)}$ at DART buoys for each of the seven source models. At the buoy 21418, the fault model M4 has the lowest mean normalized RMS misfit of 0.68 while M5 has the highest value of 1.0. This is because model M5 results in a large negative crest after the first peak shown in Fig. 4. M1 and M2 reproduced the secondary peak which most model could not reproduce, however, the two models still have relatively higher $R_{ij}^{(st)}$ even if M4 has the lowest value without reproducing the secondary peak. The first peak amplitudes of M1 and M2 are smaller than the observed first peak. This brought the higher $R_{ij}^{(st)}$. M1, M3, and M4 produces similarly lower $R_{ij}^{(st)}$ of 0.4 ~ 0.6 at buoy 21401 and 21419. At buoy 21413, which is located to the south of the earthquake source, model M1 shows the best performance with an RMS misfit of 0.4. M3, M6, and M7 also have low $R_{ij}^{(st)}$. M5 show the highest $R_{ij}^{(st)}$ at the four buoys. We compared $r_{ij}^{(st)}$ and $r_{i}^{(f_{model})}$ of the DART buoys, and found that all models produce lower $R_{ij}^{(st)}$ values at DART buoys than for region-wide values. Based on
comparison of the simulation results and observation data, our simulations are reasonable for the main
 tsunami of the 2011 Tohoku earthquake.

3.2 Southern offshore region of Korea

We collected tsunami records from tide gauges Moseulpo, Seogwipo, Geomun-do, Goheung, and Tongyeong, which are located along the southern Korean coast. We also obtained tidal data from Akune station located on the western coast of Kagoshima, Kyushu. Unlike the DART buoys, these tide gauges are located in the port, thus, we used a band-pass filter to remove high frequency (periods < 5 min) and low frequency (periods > 6 h) signals due to harbor oscillations and tidal effects. At Seogwipo and Moseulpo, located along the coast of Jeju Island, the synthetic waveforms are in good agreement with the observed waveforms, but the arrival time of the first peak is approximately 10 min faster than the observed one.

The delay times between observed and synthetic records are longer than those for DART buoys (Table 2). The first peak arrivals of models M1 and M2 more closely match the observations than other models. Model M6 produces the longest delay time at Tongyeong station (~ 22 min) whereas this model exhibits the smallest delay time at Moseulpo and Seogwipo stations. At Akune, the first peak arrival times of all models match well with the observations, even though the amplitudes are larger than the observations regardless of slip model (Fig. 8).

For $r_{ij}^{(st)}$ and $R_{ij}^{(st)}$ of the southern coast region of Korea, we applied different duration time windows for each station due to the different times taken by the tsunamis to arrive at each station. We set a time window of 200–780 min for Akune, 300–780 min for Geomun-do, Seogwipo, and Moseulpo stations, and 360–780 min for Goheung and Tongyeong stations. The seven models show minimal differences in $r_{ij}^{(st)}$ and the general trend is a near zero systematic bias (Fig. 6b). At Goheung, all models have a larger bias than other stations in the South Sea of Korea, but they are still smaller than other offshore regions such as the northwestern coast of Japan.

$R_{ij}^{(st)}$ exhibit various differences with regard to source models and stations (Fig. 7b). Model M6 has lower $R_{ij}^{(st)}$ than $R_{ij}^{(f_{model})}$ at all stations in the southern offshore region of Korea. At station Tongyeong and Akune, all other models have higher $R_{ij}^{(st)}$ values than the region-wide $R_{i}^{(f_{model})}$. The
arrival times of the first peaks are in good agreement with the observations, but the synthetic
waveforms are more amplified at these two stations. At Seogwipo and Moseulpo, $R_{ij}^{(s)}$ values of the
seven source models have the lowest and second lowest values, respectively, at these two stations.

3.3 Northwestern offshore of Japan and Eastern offshore of Korea

To study the unusual sea waves caused by the Tohoku
earthquake in the East Sea, we collected observed tsunami records from the tide gauges at
Nezugaseki, Ogi, and Wajima, located along the northwest coast of Honshu Island, Japan, as well as
the tide gauges at Sokcho, Mukho, Pohang, and Hupo, located along the eastern coast of Korea. The
records show short period oscillations (Fig. 9) with different features from the tsunamis captured by
the DART buoys and tide gauges in the southern sea of Korea. This may be because the East Sea, the
back-arc basin of the Japanese Island Arc, was co-seismically disturbed when the Tohoku earthquake
occurred. This is a similar phenomenon to the case when water in the bath experiences oscillations
when the bath is impacted from the outside. The phenomenon can be further explained using rigorous
approaches such as numerical simulations assuming a dynamic rupture model or elastic water wave
propagation, which is beyond the scope of this study.

Before comparing observed and synthetic waveforms, we applied a bandpass filter to the
signals with corner periods of 5 min and 6 h to remove unwanted signals due to tidal and harbor
effects. Nezugaseki and Ogi stations capture an increased amplitude and short period components
right after the earthquake, and Wajima station shows a slight change in sea wave height about 30 min
later (Fig. 9a). There is may be less or no seafloor displacement near Wajima compared with the other
two stations; therefore, the sea level change is seen later at Wajima. Sokcho, Mukho, and Hupo
stations also show the amplified amplitudes with short period oscillations about 30 min after the
earthquake origin time (Fig. 9b). The synthetic waveform results of of Wajima, Nezugaseki and Ogi
show a poor correlation to the observed waveforms (Fig. 10). At the beginning of the wave trains,
model M6 produced an initial negative amplitude at Nezugaseki and Ogi station, while the other
models produced positive amplitudes initially. This is due to model M6 largely producing initial
seafloor subsidence in the back-arc region whereas other models show uplift predominantly (Fig. 11).
We could not clearly determine the delay time between the observation data and synthetic data at these stations because the first peak caused by the earthquake were too small to be detected.

To calculate $r_{ij}^{(st)}$ and $R_{ij}^{(st)}$, we set a time window of a length of 90 min for Nezugaseki, Ogi, and Wajima. This time window is set to cover the short period waves that occurring coseismic period and rules out any possible inclusion of the primary tsunamis passed through the Tsugaru Strait. At these three stations, most of the source models overestimate wave amplitudes compared to the observations, except for model M6 (Fig. 6c). The seven models result in much higher $R_{ij}^{(st)}$ compared to $R_i^{(f \text{model})}$ values. Meanwhile, model M6 in particular shows significantly higher $R_{ij}^{(st)}$ at Nezugaseki than the other models (Fig. 7c).

The observed records at Sokcho, Mukho, Pohang, and Hupo tide gauges, located along the eastern coast of Korea, were also bandpass filtered using corner periods of 5 min and 6 h and compared with synthetic tsunami waveforms produced by the seven slip models (Fig. 12). For these four stations, we used a time window duration of 180 min from the origin time to include sea waves generated off the northwest coast of Japan during the coseismic period and exclude the primary tsunamis that passed into the Tsugaru Strait from the origin source area. At Mukho and Hupo, the observed wave height amplitudes increase slightly 2 h after the earthquake origin time and the synthetic waveforms also marginally amplify due to sea waves generated on the eastern region of the East Sea (Fig. 9b).

$r_{ij}^{(st)}$ show that model M6 tends to slightly underestimate amplitudes at Pohang and Mukho, but there are no systematic biases at Hupo and Sokcho (Fig. 6d). The other six models also underestimate tsunami heights with no significant discrepancy between stations. However, model M6 has a significantly higher $R_{ij}^{(st)}$ value at Pohang, while those $R_{ij}^{(st)}$ for the other three stations have smaller values than their region-wide averages $R_i^{(f \text{model})}$ (Fig. 7d). During the first 180 min, the initial subsidence in the back-arc region produced by model M6 caused a wave that appears to be out of phase with the observed wave heights, which caused the highest value of $R_{ij}^{(st)}$ among the models to occur at Pohang. M6 shows noticeably different waveforms at the stations along the eastern coast of Korea while the other six models have analogous waveforms. The effect of the initial seafloor...
subsidence can also be seen to a smaller degree at Sokcho, Mukho, and Hupo (Fig. 11).

The synthetic waveforms at these three stations also show similar features as that of
observations such as a short wave period, but they have poor agreement. Moreover \( r_{ij}^{(sr)} \) have larger

gap than other stations located in the southern coast of Korea and in the open sea and \( R_{ij}^{(st)} \) values are

a lot higher. There are several aspects affecting this mismatch. Among them, the decisive factor is that
the tidal gauges for the observed records are located within the port barrier, and the resolution of the
complicated bathymetry and geometry inside the port is typically inappropriate for regional numerical
simulations. Overall, the models effectively simulate the short-period oscillations generated in the
back-arc basin by the Tohoku earthquake.

4. Discussion

4.1 Slip model resulted in the most observation-like synthetic waveforms

Based on the three criteria that we suggested to determine a better performance in the tsunami
simulations, we suggest model M1, M2, M3 and M6 produced good results. Model M1 have short lag
time at DART buoys which is between 0 to 3 min and it became longer at the southern coast of Korea,
but still shorter than those of other models. Also, \( \epsilon_i^{(model)} \) is less bias than other models and \( R_i^{(model)} \)
has the smallest value among the seven models. M2 also shows short lag time as M1 does and small
\( R_i^{(model)} \) value, but this model overpredicted than M1. M3 resulted in mostly earlier arrivals along the
South Sea of Korea and in the case of M6, it resulted shorter lag time than the other models except at
the Tongyoeng station. Even if M3 and M6 show poor \( R_{ij}^{(st)} \) values along the coast of the East Sea,
they show good \( R_{ij}^{(st)} \) for DART buoys and tidal gages along the southern coast of Korea. Moreover,
M6 show minimum bias among the seven models.

4.2 Sensitivity of source models according to source parameters

We compare the slip models based on the results of tsunami simulations with regards to
several details such as the distribution of slip and seafloor displacement, the amount of slip and
seafloor displacement, the dimension of the fault, the size and number of sub-faults, and the location of the upper surface of the fault plane based on given fault parameter information of the fault models.

Models M1 and M2, from the inversion of the tsunami waveforms, resulted in lower $R_{ij}^{(st, model)}$ and shorter delay times than other models. Several previous simulations of the 2011 Tohoku tsunami have been conducted using various source models, including model M1 used in this study, and their results also showed that tsunami waveform inversion model M1 matched the observations most closely (Ulutas 2013; MacInnes et al. 2013). Model M2 is the advanced tsunami waveform inversion model of M1, and it exhibited the good $R_{ij}^{(st)}$ value too. Two models have fault width of the same size, but M2 has 50 km longer fault length, and its slip is distributed more northern part along the trench. They also have different amount and pattern of slip and seafloor displacement, but those discrepancies barely affect sea waves in the offshore of Korea whereas there are distinct differences between tsunamis produced by M1 and M2.

Models M3 to M5 were inverted from the finite fault inversion method using seismic data (Shao et al. 2013). Model M4 and M5 have better $R_{ij}^{(st)}$ than M3 at stations located along the northwest coast of Japan and the eastern coast of Korea. This is because the fault planes of M4 and M5 are closer to the trench axis whereas that of model M3 is located further west than the other two models. The distribution of seafloor displacement shows that model M3 generated higher seafloor displacement along the northwest coast of Japan and it caused larger wave heights. Similar characteristics were shown by model M7, in which the fault plane is further from the trench axis than in other models, leading to uplift over a broader area. The two models M4 and M5, have the same fault dimension, number of subfaults, and similar amount of maximum slip, average slip, and maximum displacement. However, their slip distribution patterns are different, and this feature made discrepancy between waveforms of two models only at DART buoys, and the feature hardly affect the tsunamis on the coast of Korea in a similar way to the case as shown in M1 and M2.

Model M6 was inverted from the finite fault inversion method using seismic data in the same manner as those of models M3 to M5. Even though M6 resulted in relatively high $R_{ij}^{(st)}$ along the coast of East Sea as what we explained previous section, this model resulted in lower $R_{ij}^{(st)}$ value than
at the all of stations located in the southern coast of Korea. The fault dimensions of M6 is the largest one and its maximum seafloor displacement is the smallest among the seven models (Table 1). M3 and M4 have the smallest fault dimension and their $R_{ij}^{(st)}$ at the southern coast are higher than the others. Hence, for better agreement with observations in the offshore of Korea, the fault dimension should be larger than 200 by 475 km. M1 and M2 have the best $R_{ij}^{(st)}$ in the same region and their fault dimensions are larger than M3 and M4.

Model M7 exhibited a substantially larger $R_{ij}^{(st)}$ value than the other six models. Specifically, it had a higher $R_{ij}^{(st)}$ at several stations in the southern coast of Korea and the northwestern coast of Japan. The wave amplitude of M7 was larger than other models and M7 over predicted at the DART buoys except for station 21413. The biggest differences between this model and the other models were the higher slip distribution along the down-dip direction from the upper limit of the fault and thus the greater distance from the trench axis of the area showing large seafloor displacement. This model is composed of the largest number and the smallest size of sub-faults among all the models considered in this study; thus, it may be able to describe slip distribution in more detail on the fault plane, but it does not mean it leads to better predictions.

In the near-field open sea, the slip distribution pattern had varying effects on the RMS misfits and the residuals, whereas in the southern coast of Korea and the East Sea, the slip distribution patterns had a weak effect. On the southern coast of Korea, the fault dimension and the amount of slip are had a larger effect on the RMS misfit between the observations and the synthetic waveforms. Therefore, tsunami waves that reach Korea may be able to provide constraining information on the extent and polarity of seafloor deformation for a reasonable finite-fault model of a tsunamigenic earthquake occurring along the off the Pacific coast of Japan.

4.3 Comparison of $R_{ij}^{(st)}$ to $R_{i}^{(f_{model})}$

There are several stations where the all source models resulted in higher $R_{ij}^{(st)}$ value than $R_{i}^{(f_{model})}$; namely, Akune and Tongyeong stations, which are located in the western coast of the
Kyushu and the southern coast of Korea, respectively. Three stations, Nezugaseki, Ogi, and Wajima are located along the northwestern coast of Japan. Fig. 13 compares the locations of Tongyeong and Akune and Moseulpo and Seogwipo, which had the lowest $R^{(st)}_{ij}$ along the southern Korean coast. Tongyeong and Akune are located in narrow channels between two islands whereas Moseulpo and Seogwipo are located along uninterrupted coastline. In this study, we used 30 arc-second bathymetry data for the tsunami simulations, which may not have sufficient resolution to represent the complicated coastline and obtain synthetic waveforms similar to the observations. On the other hand, while Nezugaseki, Ogi, and Wajima stations are located along a linear coastline (Fig 1), their $R^{(st)}_{ij}$ were among the highest in the region. In this region, the seven models produced waveforms with larger amplitudes than the observations. Fig. 11 shows the complicated contour line of the total vertical displacement offshore of northwest Japan; this synthetic seafloor displacement generated larger amplitude and shorter period synthetic wave profiles.

5. Conclusions

The tsunami caused by the 2011 Tohoku earthquake reached the southern sea of Korea by diffracting around Kyushu Island. It also co-seismically induced small sea waves with short period oscillations in the East Sea, which were captured at several tide gauges along the eastern coast of Korea. The tsunami propagated indirectly into Korean offshore due to the geographical features of the Japanese Island Arc. In this study, we performed tsunami simulations using seven different slip distribution models of the Tohoku earthquake to examine whether the slip models were able to accurately reproduce the diffracted tsunami and short-period sea waves, and to investigate tsunami features by the geomorphological characteristics of the Korean Peninsula in the offshore of Korea.

The slip distribution models reproduced reasonable waveforms at four DART buoys, 21418, 21401, 21413, and 21419. We compared synthetic waveforms with observations of six tide gauges located along the coasts of southern Korea and one tide gauge on the western coast of Kyushu Island for the diffracted tsunami. Overall, the slip models reproduce synthetic waveforms that agree well with the observations, except that their first arrival times are faster than the observations. Synthetic results at seven tide gauges along the coast of East Sea also show short-period waves, which were co-
seismically excited by the Tohoku earthquake, despite the difficulty of waveform matching due to the low resolution of coastlines and bathymetry in the near-shore region.

To determine which source model shows a better performance in the tsunami simulations, we set three criteria; the delay time between observations and synthetic waveforms, the normalized mean residual, and the normalized RMS misfit. While all of models show varying degrees of accuracy depending on the study region, according to our criteria, we suggest M1, M2, M3 and M6 give better results than others. Regarding $R_{ij}^{(m)}$ values and source parameters, we found different sensitivity depending on the coast regions. In the near-field open sea, the slip distribution pattern brought different accuracy whereas the slip pattern gives weak effects in the coast of the southern coast of Korea and East Sea. On the southern coast of Korea, fault dimension and amount of slip are more related to the RMS misfit. Hence, the tsunami observations of diffracted waves and small sea waves along the southern coast and eastern coast of Korea, respectively may be able to provide constraining information on the extent and polarity of seafloor deformation for a plausible finite-fault model of a tsunamigenic earthquake occurring along the eastern coast of Japan.

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REFERENCES


Table 1 Source parameters of the seven slip distribution models.
<table>
<thead>
<tr>
<th>Model</th>
<th>Seismic moment (Nm)</th>
<th>Epicenter</th>
<th>W (km)</th>
<th>L (km)</th>
<th>Number of sub-faults</th>
<th>Size of sub-faults (km²)</th>
<th>Max.* slip/ Ave.† slip (m)</th>
<th>Di sp. ‡ (m)</th>
<th>Inversion methodology (dataset)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>3.8 x 10²²</td>
<td>38.103N, 142.861E (JMA)</td>
<td>20</td>
<td>500</td>
<td>50 x 40/7.6</td>
<td>50 x 50/4/2</td>
<td>13.5</td>
<td>13.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(Fujii et al. 2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(tsunami wave)</td>
</tr>
<tr>
<td>M2</td>
<td>4.2 x 10²²</td>
<td>38.103N, 142.861E (JMA)</td>
<td>20</td>
<td>550</td>
<td>50 x 25/69/12</td>
<td>50 x 50/4/8</td>
<td>12.4</td>
<td>12.4</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>(Satake et al. 2013)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(tsunami wave)</td>
</tr>
<tr>
<td>M3</td>
<td>5.6 x 10²²</td>
<td>38.222N, 142.369E (preliminary USGS)</td>
<td>20</td>
<td>500</td>
<td>20 x 40/12</td>
<td>20 x 25/4/6</td>
<td>11.1</td>
<td>11.1</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>(Shao et al. 2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(teleseismic P, SH, and surface wave)</td>
</tr>
<tr>
<td>M4</td>
<td>5.84 x 10²²</td>
<td>38.106N, 142.860E (JMA)</td>
<td>20</td>
<td>475</td>
<td>20 x 25/56/12</td>
<td>20 x 25/1/3</td>
<td>15.1</td>
<td>15.1</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>(Shao et al. 2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(teleseismic P, SH, and surface wave)</td>
</tr>
<tr>
<td>M5</td>
<td>5.75 x 10²²</td>
<td>30.106N, 142.860E (JMA)</td>
<td>20</td>
<td>475</td>
<td>20 x 25/58/12</td>
<td>20 x 25/5/9</td>
<td>15.1</td>
<td>15.1</td>
<td>15.1</td>
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<tr>
<td></td>
<td>(Shao et al. 2011)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>(teleseismic P, SH, and surface wave)</td>
</tr>
<tr>
<td>Event</td>
<td>Magnitude</td>
<td>Maximum Slip</td>
<td>Average Slip</td>
<td>Maximum Total Vertical Displacement</td>
<td>Location</td>
<td>Depth</td>
<td>Dip</td>
<td>Strike</td>
<td>Slip</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
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<td>--------------</td>
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<td>----------</td>
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<td>-----</td>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>M6</td>
<td>4.9 x 10^{22}</td>
<td>38.222N, 142.369E</td>
<td>26 x 625</td>
<td>13 x 20 x 33/5.6 5.5</td>
<td>(Hayes et al. 2011) (USGS)</td>
<td>26 0 625 25 25</td>
<td>Seismic inversion (teleseismic P, SH, and surface wave)</td>
<td></td>
<td></td>
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<tr>
<td>M7</td>
<td>3.6 x 10^{22}</td>
<td>38.32N, 142.37E</td>
<td>21 x 600</td>
<td>14 x 15 x 40/8.3 8.5</td>
<td>(Ammon et al. 2011) (USGS)</td>
<td>21 0 600 40 15</td>
<td>Seismic and GPS inversion (teleseismic P and Rayleigh wave, hrGPS)</td>
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<td></td>
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</table>

*Maximum amount of slip
†Average amount of slip
‡Maximum amount of total vertical displacement
Table 2 Delay time between observations and synthetic wave profiles of the seven source models.

<table>
<thead>
<tr>
<th>Station</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
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<tbody>
<tr>
<td>DART 21401</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>-3.0</td>
<td>-2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>DART 21413</td>
<td>0</td>
<td>2.0</td>
<td>-1.0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>-1.0</td>
<td>0</td>
</tr>
<tr>
<td>DART 21418</td>
<td>1.0</td>
<td>0</td>
<td>2.0</td>
<td>1.0</td>
<td>-1.0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>DART 21419</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Goheung</td>
<td>-6.0</td>
<td>-11.0</td>
<td>-15.0</td>
<td>-18.0</td>
<td>-16.0</td>
<td>-6.0</td>
<td>-10.0</td>
</tr>
<tr>
<td>Moseulpo</td>
<td>-7.0</td>
<td>-6.0</td>
<td>-11.0</td>
<td>-9.0</td>
<td>-7.0</td>
<td>-8.0</td>
<td>-9.0</td>
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<tr>
<td>Seogwipo</td>
<td>-6.0</td>
<td>-6.0</td>
<td>-10.0</td>
<td>-9.0</td>
<td>-7.0</td>
<td>-6.0</td>
<td>-8.0</td>
</tr>
<tr>
<td>Tongyeong</td>
<td>-15.0</td>
<td>-15.0</td>
<td>-17.0</td>
<td>-17.0</td>
<td>-15.0</td>
<td>-23.0</td>
<td>-16.0</td>
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<tr>
<td>Akune</td>
<td>0</td>
<td>0</td>
<td>-10.0</td>
<td>-5.0</td>
<td>-1.0</td>
<td>-3.0</td>
<td>-3.0</td>
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<tr>
<td>Ave. DT</td>
<td>-4.7</td>
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<td>-7.7</td>
<td>-7.5</td>
<td>-6.9</td>
<td>-6.1</td>
<td>-5.2</td>
</tr>
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</table>

Ave. DT* Average delay time of 9 stations for each model
Figure 1. Distribution of earthquakes and tsunami observation stations used for analysis in this study. Red star represents the epicenter of the 2011 Tohoku earthquake and orange stars are the locations of earthquakes occurring along the western offshore of Japan. Triangles indicate station locations of observation data used in this study. Yellow triangle symbols in the deep-sea area are DART buoys, and light orange triangles in the coast areas are tide gauges.
Figure 2. Seven slip distribution models of the 2011 Tohoku-oki earthquake. Light gray solid line shows the depth of the subducting Pacific plate with the intervals of 20 km and dark gray solid line is for the plate boundaries. (a) Fujii et al. (2011), (b) Satake et al. (2013), (c) to (e) Shao et al. (2011), (f) Hayes (2011), (g) Ammon et al. (2011).
Figure 3. Total vertical seafloor displacement distributions of seven source models. Red and blue colors represent uplift and subsidence, respectively. Light gray solid and dotted lines are the contour lines of uplift and subsidence at 1.5 m intervals, respectively. Authors of the seven models are given in Fig. 2.
Figure 4. Comparison of simulated and observed tsunami waveforms at the DART buoys. Gray region represents the duration of the time window. Locations of DART buoys are shown in Fig. 1 and slip distributions of fault models M1–M7 are given in Fig. 2.
Figure 5. Delay time between observation and synthetic wave of the first peak at 10 stations for the seven models.
Figure 6. Mean normalized residuals of (a) the DART buoy stations, (b) tide gauges in the southern offshore region of Korea, (c) tide gauges on the northwest coast of Japan, and (d) tide gauges on the east coast of Korea. Gray rectangle is the total mean normalized residual for each model. Locations of DART buoys and tide gauges are given in Fig. 1. Slip distributions of the fault models M1 ~ M2 are shown in Fig. 2.
Figure 7. Mean normalized RMS misfit of (a) the DART buoy stations, (b) tide gauges in the southern offshore region of Korea, (c) tide gauges on the northwest coast of Japan, and (d) tide gauges on the east coast of Korea. Gray rectangle is the total mean normalized RMS misfit for each model. Locations of DART buoys and tide gauges are given in Fig. 1. Slip distributions of the fault models M1 ~ M2 are shown in Fig. 2.
Figure 8. Comparison of synthetic waveforms and observations at stations located on the south coast of Korea and the west coast of Kyushu Island. Gray region represents the duration of the time window. Locations of DART buoys and tide gauges are given in Fig. 1. Slip distributions of the fault models M1 ~ M2 are shown in Fig. 2.
Figure 9. Observations caused by the 2011 Tohoku earthquake in the East Sea (a) at Nezuegaseki, Ogi, and Wajima stations along the northwest coast of Japan. (b) at Sokcho, Mukho, Hupo, and Pohang stations along the eastern coast of Korea. Blue lines indicate the origin time of 2011 Tohoku earthquake. Locations of the tide gauge stations are shown in Fig. 1.
Figure 10. Waveform comparison of synthetic and observations at stations located on the southwest coast of Honshu, Japan. Gray region represents the duration of the time window. Locations of DART buoys and tide gauges are given in Fig. 1. Slip distributions of the fault models M1 ~ M2 are shown in Fig. 2.
Figure 11. Contour lines of total vertical seafloor displacement throughout the back-arc basin for the seven fault models. The contour line has an interval of 1 cm. Note that contour lines of dark blue ranges between -0.3 m and -0.03. Slip distributions of the fault models M1 ~ M7 are given in Fig. 2.
Figure 12. Comparison of synthetic waveforms and observations at stations located on the east coast of the Korean Peninsula. Gray region represents the duration of the time window. Locations of DART buoys and tide gauges are given in Fig. 1. Slip distributions of the fault models M1 ~ M2 are shown in Fig. 2.
Figure 13. Detailed location of (a) Tongyeong, (b) Akune, (c) Moseulpo, and (d) Seogwipo tide gauges using 30 arc-seconds topography data.