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<th>Journal:</th>
<th>Geophysical Journal International</th>
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<tr>
<td>Manuscript ID</td>
<td>GJI-S-16-0004</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Research Paper</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>04-Jan-2016</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Baag, So-Young; Seoul National University, School of Earth and Environmental Sciences Rhie, Junkee; Seoul National University, School of Earth and Environmental Sciences; Yoo, Seung-Hoon; Weston Geophysical Corporation Kim, Seongryong; The Australian National University, Research School of Earth Sciences Kim, Satbyul; Pukyong National University, Department of Earth and Environmental Sciences Kang, Tae-Seob; Pukyong National University, Department of Earth Environmental Sciences</td>
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<tr>
<td>Keywords:</td>
<td>Tsunamis &lt; GENERAL SUBJECTS, Early warning &lt; SEISMOLOGY, Earthquake source observations &lt; SEISMOLOGY, Continental margins: convergent &lt; TECTONOPHYSICS, Subduction zone processes &lt; TECTONOPHYSICS</td>
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**Rapid determination of multi-dip rupture processes based on a 3D structure for tsunami early warning with an application to the 2011 Tohoku-Oki earthquake**

So-Young Baag¹, Junkee Rhie¹, Seung-Hoon Yoo², Seongryong Kim³, Sat-Byul Kim⁴, and Tae-Seob Kang⁴

¹ School of Earth and Environmental Sciences, Seoul National University, Seoul, 08826, Republic of Korea
² Weston Geophysical Corporation, 181 Bedford St. #1, Lexington, Massachusetts, 02420, USA
³ Research School of Earth Sciences, The Australian National University, Canberra ACT 2601, Australia
⁴ Department of Earth and Environmental Sciences, Pukyong National University, 599-1 Daeyeondong, Nam-gu, Busan 48513, Republic of Korea

**Corresponding author:**

Junkee Rhie; School of Earth and Environmental Sciences, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, 08826, Republic of Korea; Phone) +82-2-880-6731; Fax) +82-2-883-1572; E-mail) rhie@snu.ac.kr

**Abbreviated title:** Rapid determination of multi-dip rupture processes for tsunami early warning
SUMMARY

In order to mitigate the tsunami disasters caused by megathrust earthquakes, early warning systems utilizing fast and accurate determination of the earthquake’s rupture process are essential. In this study, we develop a new method for rapid determination of rupture processes on megathrust faults applicable to tsunami early warning by constructing the multi-dip finite fault models and calculating 3D Green’s functions well before the earthquake.

The large-magnitude tsunamigenic earthquakes occur on subduction zones’ plate interface where the locations and topographies are already known. Therefore, we constructed multi-dip megathrust fault models composed of subfaults using the reliable geometries of the plate interfaces in the global subduction zones. For all available subfault-station pairs of multi-dip fault models and global broadband seismic networks, teleseismic Green’s functions of full waveforms in 3D global earth structure were computed using the spectral element method. The result forms a Green’s function database composed of 2.7 million of Green’s functions, such that effects in 3D wave propagations and complex fault geometries can be accounted in estimated rupture processes promptly after the earthquake. The rupture process along the finite fault models can be computed by the non-negative least-square inversion technique in a short time right after a megathrust earthquake using the Green’s function database and broadband teleseismic data set. The resulting slip distribution model can be applied to tsunami simulation, enabling the fast and accurate prediction of tsunami waves. The applicability of this method is tested with the Great 2011 Tohoku-Oki, Japan, earthquake. The result showed similar slip distribution and maximum amplitudes to those of other studies in the rupture process. The synthetic tsunami waveforms computed based on the slip distribution from the finite fault
modeling were not only favorably compared with the observations recorded at Deep-

-ocean Assessment and Reporting of Tsunami (DART) buoys located to the east of

-Honshu, Japan, but also showed better fit to the observation than the ones computed

-based on more conventional methods that involve the slip distribution from a 1D

-velocity model and a single-dip fault model.
1. INTRODUCTION

The tsunamis generated by megathrust earthquakes in subduction zones devastate large areas near and far from the source region across the globe. The scales of damages and casualties caused by tsunamis are very serious. Recent examples are the Great Sumatra-Andaman earthquake of Mw9.3 occurred on the 26 December 2004 off the west coast of the northern Sumatra and the Great Tohoku-Oki earthquake of Mw 9.0 on 11 March 2011 near the east coast of Honshu, Japan (Simons et al., 2011, Tajima et al., 2012, Ammon et al., 2005, Lay et al., 2005). Most of the serious damages and casualties came from tsunamis in the two great earthquakes (Ammon et al., 2005, Tajima et al., 2012).

In order to mitigate such disasters, it is necessary to develop a tsunami early warning system. Fortunately, the propagation speeds of the tsunamis are slower compared with the speeds of seismic wave propagation, and thus it is possible to anticipate the generation of tsunamis based on the information on source parameters determined by the analysis of early arriving seismic waves right after the occurrence of a large earthquake in a subduction zone. However, the precise decision on the possibility of excitation, size and characteristics of the tsunami require the accurate information of the rupture processes and slip distributions on the megathrust faults (MacInnes et al., 2013, Tajima et al., 2012, Ide et al., 2011, Ammon et al., 2005).

Since seismic networks are not established near to most of megathrust region, the information can usually be obtained by analysis of teleseismic data.

The rapid determination of the rupture process of the earthquakes along megathrust faults can be done through a few methods of analysis such as back-projection, and inversions of body wave, surface wave, and W-phase. The back-projection method usually uses high-frequency teleseismic P waveforms for observing high-frequency
radiation in the rupture process. The information obtained from the back-projection
method is applicable to finding the distribution of high-frequency radiation sources
(Ishii et al., 2005) in the megathrust fault, and does not present the actual slip
distribution that can generate a tsunami, because it does not quantitatively account for
the Green’s function influences on seismic wave energy partitioning (Lay et al.,
2010b). Body wave inversion utilizes teleseismic P and S waves generated by an
earthquake. The P wave arrives at stations earlier than any other seismic phases,
which would be useful for early warning of disasters. It is also characterized by being
sensitive to details of the slip distribution on the fault, but not to overall distribution
of slips with large spatial scale (Lay et al., 2010a). Inversions using the waves
sometimes result in strong trade-offs between the rupture velocities and spatial range
of slip distribution, due to lack of resolved directivity caused by larger wave velocity
compared to the rupture velocity. Thus the spatial extent of slip can be controlled by
the rupture velocity if there are no additional constraints (Lay et al., 2014). W-phase
carries long-period information of an earthquake and theoretically represents both
near- and far-field long-period wavefield (Kanamori and Rivera, 2008). Since the W-
phase arrives with P wave train, much faster than surface waves, it has been proven
effective in fast and accurate inversions for moment tensor solutions of large
earthquakes as point sources and is suggested useful in early warnings for possible
tsunamis. However, the W-phase is not routinely used in determination of slip
distributions of large earthquakes except for a limiting case of the work by
(Benavente and Cummins, 2013, Duputel et al., 2011), probably due to its simplicity
of waveform with small amplitude that could be a drawback in assessment of the
spatiotemporal variation of slip distribution. Surface waves have longer periods and
larger amplitudes than body waves, therefore they are efficiently used in detection of
relatively broad and larger spatial extent of slips leading to slip distribution of the entire fault (Lay et al., 2011). Since various phase velocities of the dispersive surface wave are smaller than those of body waves and very close to the typical rupture speed along the fault, the waves exhibit large rupture directivity effects. Azimuthally dependent effective source time functions that are carried by the surface wave can be used for resolving the rupture length and smooth variation of the seismic moment (Ammon et al., 2006). Tsunamis can be generated by fault rupture processes of megathrust earthquakes, where slip variations of the fault range from relatively fine details detectable by teleseismic body wave analysis to relatively broad and large spatial extent of slips by teleseismic surface wave, as shown by results of previous works (Yue et al., 2014). The contribution of slip variation inferred from body waves and the one from the surface waves to the tsunami waveforms are compromising to each other (Lay et al., 2010a). Therefore, the teleseismic full waveform inversion is more promising compared to the inversion using the body wave or surface wave only. In the current study, we attempt to approach the problem with finite fault inversion using broadband full-waveform seismic records including teleseismic body waves and surface waves.

The main factors that determine the accuracy of inversion of finite fault rupture process are: observation data, Green function, and fault geometry. For a given teleseismic full waveform data, the ones that we can control are the fault geometry model and the Green's function. The most frequently used method of finite fault modeling involves designing the single-dip finite fault geometry based on moment tensor solutions or other source information available after the occurrence of the earthquake and calculating Green’s functions based on the fault geometry (Ammon et al., 2005, Avouac et al., 2015, Banerjee et al., 2005, Lay et al., 2010a, Lay et al.,
However, the single-dip scheme for simulation of megathrust faults are not realistic, because the fault surfaces are curved with variable dips (Lay et al., 2012). Thus we constructed multi-dip finite fault models consisting of subfaults for megathrust fault segments in globally distributed eleven subduction zones, utilizing the 3D plate interface model Slab 1.0 of United States Geological Survey (USGS) (Hayes et al., 2012). The Green’s functions are usually calculated using 1D earth models (Ammon et al., 2006, Ammon et al., 2011, Lay et al., 2010a, Lay et al., 2010b, Lay et al., 2011, Yue et al., 2014). However, synthetic seismograms computed using the 1D velocity model (PREM) (Dziewonski and Anderson, 1981) shows much larger deviations from observed teleseismic data than those using 3D velocity model S20RTS (Ritsema, 2004, Ritsema et al., 1999) even in the signals with long period of a few hundred seconds (Figure 9 of Tromp et al. (2008)). We compute Green’s functions in 3D velocity model, S362ANI (Kustowski et al., 2008) using spectral element method (SEM, Tromp et al. (2008)) for source-station pairs of all the subfaults in the designed megathrust multi-dip fault models in the world and hundreds of globally distributed broadband seismic stations. This results in setting-up of a global Green’s function database composed of about 2.7 millions of Green’s functions.

Even though Green’s function calculations using these 3D velocity models are more accurate, they are very time-consuming and inefficient, especially in situations where the timely availability of the finite fault inversion is crucial. Therefore, we alleviate this problem by calculating and storing the Green’s functions well before the occurrence of the megathrust earthquake. Thus, the rupture process can be readily calculated as soon as the earthquake occurs using the Green’s functions in the storage device.
This study presents a fast method to compute the rupture distributions in finite fault inversion of megathrust earthquakes occurring in major subduction zones in the world, using a global Green’s function database computed by spectral element method for a 3D earth model (S362ANI) and the multi-dip (Mdip) fault models derived from Slab 1.0, and tests the method’s applicability on 2011 Tohoku-Oki earthquake. The application shows that the scheme of 3D velocity model and multi-dip fault plane produces more accurate results than the ones involving 1D velocity and single-dip fault model for prediction of recorded tsunami observations.

2. MEGATHRUST FAULT MODELS AND GREEN’S FUNCTIONS

2.1. Construction of Megathrust Fault Models

The slip of megathrust fault is confined to a shallow portion of the plate interface down to about 50 km of depth from the trench in a subduction zone (Lay et al., 2012). A large sudden slip along the fault by a megathrust earthquake can generate a disastrous tsunami wave in addition to seismic waves propagating the whole earth (Lay and Bilek, 2007, Lay et al., 2012). For a reliable result of the full waveform inversion for rupture process of the megathrust fault, *a priori* of the fault structure is important. We construct large-scale fault geometry models of global megathrust regions based on the information of Slab 1.0, the three-dimensional numerical model of global subduction geometries (Fig. 1) (Hayes et al., 2012). The Slab 1.0 is the first and only model that represents 85% of the global subduction zones in detail. The global subduction zones in Slab 1.0 are composed of 13 regions. We chose 11 regions from them for megathrust fault geometry models focusing on the circum-Pacific region: Alaska-Aleutians (ALU), Cascadia (CAS), Izu-Bonin (IZU), Kermadec-Tonga.
(KER), Kamchatka-Kurils-Japan (KUR), Mexico (MEX), Philippines (PHI), Ryuku (RYU), South America (SAM), Solomon Islands (SOL), and Santa Cruz Islands/Vanuatu/Loyalty Islands (VAN) (Fig. 1). We divide the regions into multiple fault segments with different sizes based on the curvatures of the trench (Fig. 1 and Table 1). In the inversion process for slip distribution of a megathrust earthquake, a fault segment where the hypocenter is located is chosen for a finite fault modeling, and additional nearby segments of megathrust fault model are also chosen depending on the seismic magnitude of the earthquake. The fault model of each segment consists of subfaults with the same strike but with systematically different dips along the dip direction. Thus the model has a single strike direction and piecewise variable dips along the dip direction. The subfault size of megathrust faults for inversion of slip distributions usually varies from smaller size of $15 \text{ km} \times 15 \text{ km}$ to larger size of $100 \text{ km} \times 50 \text{ km}$, depending on the purpose (Ammon et al., 2011, Tang et al., 2012, MacInnes et al., 2013). Tsunami waves are less sensitive to details of localized slip due to intrinsic low frequency contents (Yue et al., 2014). Therefore, the subfault size for computation of the tsunami can be a larger size ranging from $40 \text{ km} \times 40 \text{ km}$ to $100 \text{ km} \times 50 \text{ km}$ (Fujii, 2011, Saito et al., 2011, Gusman et al., 2012, Tang et al., 2012, Satake et al., 2013, Wei et al., 2013). In this study, the size of the subfault was determined to be $50 \text{ km} \times 50 \text{ km}$, considering large magnitudes of the events and the frequency range of the waveform used in the inversion. The procedure of constructing a fault geometry model of a segment is as follows.

The locations of the intersection line between the fault surface and the sea floor at a trench is extracted from Slab 1.0. The extracted location of the curved trench line is approximated to a linear function with length of 400-800 km (smaller in the case of large curvature) using piecewise linear interpolation technique. The linear line
corresponds to the near-trench line of a fault segment model. In order to simplify the
constructed fault model, the average depth along the trench is used as the depth of the
intersection line. Thus, the latitudes, longitudes and the depths of intersecting points
between the sea floor and the surface of the fault segment are obtained together with
the corresponding strike direction. Then to derive the coordinates of the fault segment
along the dip direction, coordinates of the plate interface point data from Slab1.0
model are projected to a vertical plane perpendicular to the trench direction or the
strike direction. Using the plate interface points in the projected coordinates, a
piecewise linear function with a few line segments of length 50 km is determined
through the least square polynomial approximation and piecewise linear interpolation.
These line segments of 50 km in length correspond to traces of planes of subfaults in
dip directions. The slope of a line segment corresponds to the dip of the subfault. The
fault is subdivided in the strike direction by the length interval 50 km of a subfault.
The resulting faults have the maximum depth values up to 100 km, which
sufficiently covers shallow, near-trench region of tsunami-generating domain, central
region with large slip, low short-period energy domain, and down-dip region with
modest-slip, high short-period energy domain. This procedure is done for every
megathrust fault segment around the Pacific (Fig.1).

2.2 Computations for Green’s function set
In order to get accurate rupture processes of the megathrust from the inversion of
recorded full waveform data, the earth model for computation of synthetic
seismogram needs to be close to the actual earth structure. The importance of the
earth model can be found from the comparisons of recorded broadband full waveform
with synthetics computed by SEM using 1D PREM model and 3D model for the case
of the 2011 Mar. 9 Mw7.3 near-east-coast Honshu, Japan, earthquake (A foreshock of
the 2011 Mar 11 Mw9.0 Tohoku-Oki, Japan earthquake) (Fig. 2). For the 3D earth
model, we use the 3D S-wave velocity model S362ANI (Kustowski et al., 2008),
associated 3D P-wave velocity model for the mantle structure, and 3D CRUST2.0
velocity model (Bassin et al., 2000) for the crust. This combination of 3D velocity
models for the crust and mantle is also used in all synthetic seismogram computations
for 3D velocity structure in this research. The comparison between the observed and
synthetic vertical component seismograms (Fig. 2) filtered with passband of 50-500
seconds shows that there are large deviations of waveforms for the synthetics in 1D
model compared to those in 3D model, as stated in the previous section.

In our inversion for slip process of the megathrust fault, the strike and dip of each
subfault are given as pre-determined values from design of the fault model. However,
the rake and seismic moment at each subfault are variable and to be solved in the
inversion process. With the two orthogonal rake angles, 45˚ and 135˚, used as
reference rake directions or coordinate axes of slip motions on the subfault, any slip
motion on the subfault can be a linear combination of those in the two directions. The
assumption of thrust fault mechanism can be realized by the constraint of nonnegative
values of the slip components along the two directions. The slip motion on each
subfault contributes to displacements at seismic stations. In this study, three-
component (EW, NS, and Z) Green’s functions at a station are defined as responses of
the slip motion in one of the rake directions on a subfault as a point source with a unit
seismic moment of $1 \times 10^{20}$ dyne·cm. The Green’s functions with an impulse source
time function are calculated using SEM in 3D earth model described above and were
convolved with a proper source time function corresponding to the subfault to get
Green’s functions with a finite source time duration (Hereafter, we call it simply
Green’s functions. The shape of the source time function is an isosceles triangle with duration of 50 s and the covered area by the function in time domain is a non-dimensional unity.

In order to be readily used in the inversion for the rupture process right after a megathrust earthquake in a subduction zone, Green’s functions for all the subfault-station pairs are computed and stored before the earthquakes. These pairs include subfaults in all the segments of prescribed subduction zones in the world and seismic stations of worldwide networks of GSN, GEOSCOPE, GEOFON, and MEDNET (Fig. 3). With the 2606 modeled subfaults, 177 stations, 2 rake directions and 3 components, the total number of Green functions calculated are 2,767,572.

3. INVERSION FOR SLIP DISTRIBUTION

3.1. Methods for the Inversion

The synthetic seismogram at a station can be represented by a linear combination of the slip responses of all subfaults on the finite fault surface. For given slips or seismic moments with rake directions on all the subfaults, the synthetic seismogram can be calculated by

\[ u_i(t_j) = \sum_{k=1}^{N} \left[ M_k^{(45)} G_{ik}^{(45)} (t_j - \Delta t_k) + M_k^{(135)} G_{ik}^{(135)} (t_j - \Delta t_k) \right] \]

where

\[ M_k^{(45)} = M_k \cos(\lambda_k - 45^\circ) \]
\[ M_k^{(135)} = M_k \sin(\lambda_k - 45^\circ) \] (1)

Where \( u_i(t_j) \) is the \( i \)’th component amplitude of the 3-component (NS, EW and Z) displacement seismograms at time \( t_j \) with \( j = 1 \sim N_j \). Indices \( k \) represent sequential numbers assigned to subfaults for identifications with \( k = N_k \), corresponding to the
the total number of subfaults. $M_k^{(r45)}$ and $M_k^{(r135)}$ are seismic moment components in reference rake directions $45^\circ$ and $135^\circ$, respectively, for $k$’th subfault, presented in terms of the unit seismic moment. Functions $G_k^{(r45)}(t_j)$ and $G_k^{(r135)}(t_j)$ are $i$’th component amplitudes of the Green’s functions at time $t_j$ for the $k$’th subfault with reference slip rake directions $45^\circ$ and $135^\circ$, respectively. These Green’s functions have the isosceles triangular source time function and a unit seismic moment of $1 \times 10^{20}$ dyne·cm as defined above. $\lambda_k^{(r)}$ is the rake angle of the $k$’th subfault and $\Delta t_k$ is the time delay due to the rupture propagation from the hypocenter to the center of the $k$’th subfault.

For the inversion process using the least-square method, synthetics in the matrix form of the equation (1) is equated to the observed seismograms in the form of column matrix $\mathbf{d}$, and regularization conditions for minimum moment components and Laplace smoothness are attached to stabilize the inversion numerically, such that

$$
\begin{bmatrix}
G^{(r45)} & G^{(r135)} \\
\lambda_s \mathbf{L} & \lambda_d \mathbf{I} \\
\end{bmatrix}
\begin{bmatrix}
M^{(r45)} \\
M^{(r135)}
\end{bmatrix}
= 
\begin{bmatrix}
\mathbf{d} \\
0
\end{bmatrix}
$$

(2)

Here, $G^{(r45)}$ and $G^{(r135)}$ are matrices composed of Green’s function elements $G_k^{(r45)}(t_j - \Delta t_k)$ and $G_k^{(r135)}(t_j - \Delta t_k)$, respectively, with dimension $(3N_s \cdot N_i) \times (2N_k)$. The factors 3 and 2 in the matrix dimension are for 3 components of seismograms and 2 reference rake directions, respectively, and the parameter $N_i$ represents the total number of stations. $M^{(r45)}$ and $M^{(r135)}$ are column matrices composed of elements $M_k^{(r45)}$ and $M_k^{(r135)}$, respectively. The column matrix $\mathbf{d}$ is for the observed data time series with dimension of $(3N_s \cdot N_i)$. $\mathbf{L}$ represents a matrix containing the Laplacian operator for roughness regularization, and $\lambda_s$ and $\lambda_d$ represent coefficients for smoothing and damping, respectively. The roughness regularization is done separately.
for the two moment components corresponding to the two reference rakes. The difference between a moment component at a subfault and the average of those values at the surrounding nearest 8 subfaults is used as the Laplacian of the moment component at the subfault, rather than using the nearest 4 subfaults in order to have a stable constraint. In the computation, the technique of non-negative least-square (NNL) method (Lawson and Hanson, 1995) is used to restrain the seismic moment and corresponding slip values to be positive. The estimated solutions $M_k^{(r45)}$ and $M_k^{(r135)}$ are divided by $\mu A_{\text{sub}}$ to get the slip component $s_k^{(r45)}$ and $s_k^{(r135)}$, where $\mu$ and $A_{\text{sub}}$ represent the shear modulus and the area of a subfault, respectively. Since the subfault area is fixed, slip amounts are dependent on the shear modulus. The varying shear modulus values with depth are based on S362ANI’s reference earth model, STW105 (Kustowski et al., 2008). Then the slip and orientation at each subfault are obtained from the two seismic moment components at each subfault using the equations:

$$s_k = \left[ \left( s_k^{(r45)} \right)^2 + \left( s_k^{(r135)} \right)^2 \right]^{\frac{1}{2}}$$

and

$$\lambda_k^{(r)} = \cos^{-1} \left( \frac{s_k^{(r45)}}{s_k} \right) + 45^\circ.$$  

In order to check the quality of the inversion, synthetic seismograms are computed based on the estimated distribution of seismic moments and rake angles of subfaults using Eq. (1) and compared with data. As a criterion of the quality, a variance reduction defined by

$$V_R = \left[ 1 - \sum_i \frac{[\text{data}(t_i) - \text{synt}(t_i)]^2}{\sum_i [\text{data}(t_i)]^2} \right]^{\frac{1}{2}}$$ (3)
is used, where \(\text{data}(t_i)\) and \(\text{synt}(t_i)\) represent point values of time series of the observed and synthetic seismograms, respectively, for all components and stations used in the inversion.

3.2. Pre-process for the inversion

A couple of \textit{a priori} parameters are needed in the linear inversion: rupture velocity and subfault rupture duration time. Both parameters are usually determined through process of multiple experimental inversions in search for the values that yield the largest variance reduction. However, the search for the optimal values of the parameter in the inversion process can be time-consuming and can lead to inefficiency in application to tsunami early warning. On the other hand, a representative value of the rupture velocity in each of the relatively well-studied subduction regions (i.e. Chile, Tohoku, etc.) can be obtained by the weighted average of the values from prior researches. The global average of the rupture velocity is assumed to be the average of the representative values of the subduction regions and is estimated to be 2.5 km/s. In the inversion process, both types of rupture velocities can be used, even though we used the global average value in this study. If a megathrust earthquake occurs in one of the subduction zones with a representative rupture velocity of the region, then it can be used in the inversion process, but for cases otherwise, the approximate value of global average is used.

Subfault rupture duration time and subfault size used in the inversion for slip distribution are different from one research to another. Ranges of subfault sizes and subfault rupture durations commonly used are 10-50 km and 10-65 s, respectively. The ratio of the duration with respect to the size tends to be roughly around 1, and the ratio could be affected by the effect of repeated ruptures with delayed time within the
subfault. The subfault rupture duration depends on property of the megathrust earthquake source zone, and usually increases with the size of the subfault. For subfault size about 50 km x 50 km, this study uses subfault rupture duration time of 50 s, which is within the reported range.

Before the occurrence of a megathrust earthquake, all the Green’s functions corresponding to worldwide station-subfault pairs are filtered by a pass-band of 50-500 seconds in order to remove high frequency and very low frequency signals, and then are down-sampled to the time interval of 10 seconds. These modified subfault wave functions are stored in a large memory storage device and are ready to be used in constructing synthetic seismograms for inversion of observed seismograms.

Right after the occurrence of a large earthquake in one of the megathrust region, the fault segment where the hypocenter is located is determined using the preliminary information of the earthquake. Then the subfault that harbors the hypocenter within the fault segment is located. Then the depth of the earthquake is projected to the modeled fault surface, assuming the megathrust earthquakes always occur on the modeled surface. We assume that the rupture of the fault initiates from the approximate hypocenter and propagates along the fault surface with circular rupture front, and each subfault surrounding the hypocenter ruptures when the rupture front arrives at the center of it. The distances between the hypocenter and all the subfault’s centers along the fault surface were calculated, and divided by the rupture velocity to obtain the delay time relative to the rupture initiation time at the hypocenter. Then the modified subfault wave functions mentioned above were delayed in time according to the rupture propagation from the hypocenter point to the center of the subfault. In actual computation, this time-shift process of each Green’s function was done in Fourier domain by shifting phases corresponding to the delay time. The rupture
velocity during the fault’s rupture is assumed to be constant, and there is no repeated
activation of ruptures at any part of the fault in this study.

4. Tests and Application

4.1. Test of the Inversion Algorithm using Synthetic Rupture Model

Using the inversion process described above, a test of the inversion process was
done with an artificial rupture process with a spatiotemporal slip distribution. The
hypocenter was put at the center of a subfault near the middle of the megathrust fault
model (Fig. 4) for the Honshu segment in the Kamchatka-Kuril-Japan subduction
region (Fig. 1, Table 1). The hypothetical rupture distribution was constructed by
assigning slips corresponding seismic moments and rake angles to all the subfaults on
the finite fault. The rupture velocity of 2.5 km/s is assumed in calculation of delay
times of Green’s functions, i.e., the time corresponding to the rupture propagation
from the hypocenter to each center of subfault.

The three-component synthetic seismograms at 13 GSN stations were computed
using the source parameters of subfaults such as slips, rakes, and delay times
Corresponding to the rupture propagation. They were band-pass filtered between
50–500 seconds and used as a hypothetically observed data set. Then the full
waveforms were inverted for slip components of subfaults using Green’s functions
already stored in the memory system, as described in sections 3.1 and 3.2. The slip
distribution of the inversion result is exactly the same as the originally designed
distribution (Fig. 4).

4.2 Application to Slip Distribution of 2011 Tohoku-Oki Earthquake
The Great 2011 $M_w$9.0 Tohoku-Oki earthquake occurred on March 11, 2011 at 5:46:24 GMT. Its hypocenter was located 38.297º N, 142.372º E, and 30 km depth (USGS). It is reported that the source area of large slip with long-period radiation is located at shallow plate interface and the area of modest slip with high frequency radiation is limited to area of deeper depths (Tajima et al., 2012). Using the methods described above, the inversion of full-waveform for the slip process of the Great 2011 Tohoku earthquake was performed in this study.

In order to perform the waveform inversion for slip distribution of the great 2011 $M_w$9.0 Tohoku-Oki earthquake, 13 stations covering the azimuth uniformly are selected from 22 available stations that have relatively low noise signals (Fig. 5). The data set of these stations and corresponding Green’s functions are pre-processed as described in the section 3.2 before the inversion. This study makes use of global average rupture velocity of 2.5 km/s, assuming that there is no information known for the rupture of fault segment prior to the 2011 Tohoku-Oki earthquake. A least-square inversion of the waveforms is done in the way described in section 4.1 using the 3D velocity model S362ANI (3Dv) and multi-dip (Mdip) fault model based on Slab1.0 (Scheme 3Dv-Mdip), and slip distributions are obtained. Synthetic seismograms are also computed for the slip distributions determined by the inversion. Variance reductions are calculated for the waveform similarities between the waveforms of data and synthetics.

The inversion result for the scheme 3Dv-Mdip (Fig. 6) shows a predominant slip distribution on the central upper half of the fault with maximum value of 47 m near the trench. Most of the slip directs toward ESE and moment magnitude is 9.053. The overall slip distribution is consistent with other studies (Ide et al., 2011, Koper et al.,
Two examples of waveform comparisons at stations ALE and LVZ are shown in Fig. 6. The variance reduction value is 55.18%.

### 4.3 Comparison of Slip Distribution with Finite Fault Modeling using Different Earth and Slab Models

Finite fault modeling and inversion can be done with many different earth models and fault geometries. The most conventional methods of finite fault modeling make use of 1D earth model with single-dip fault model based on CMT solution. However, these models are less realistic compared to 3D earth and multi-dip models. To test the effect of earth and fault geometry models on the finite fault inversion and tsunami simulation, the inversions are done for the four schemes corresponding to combinations of two velocity models and two fault geometry models. The two velocity models are 3D S362ANI (3Dv) and 1D PREM (1Dv). The two fault geometry models are multi-dip (Mdip) fault model with variable dips based on Slab1.0 and single-dip (Sdip) fault model with only a dip based on CMT solution (Fig. 7). Thus the four combinations of schemes for velocity models and fault geometry models are 3Dv-Mdip, 3Dv-Sdip, 1Dv-Mdip, and 1Dv-Sdip. The same smoothing was applied to all four schemes.

Characteristic features of the inversion results for the scheme of 3Dv-Mdip are described above, and the other three cases are as follows:

1. In the case for 1Dv-Mdip scheme, larger slips are distributed in the central upper part of the fault, but the area is a little narrower in strike direction and deeper than the case for 3Dv-Mdip (Fig. 8). The maximum slip is 40 m and the horizontal direction of subfault slips converge towards ESE direction. Moment magnitude is 8.89, smaller than the case of the 3Dv-Mdip. Two examples of waveform comparisons at stations
ALE and LVZ are shown in Fig. 8. The variance reduction value is 47.51%. (2) In
the scheme of 3Dv-Sdip, most of subfault slip directs toward the east with maximum
slip of 60 m (Fig. 9). The moment magnitude is 9.017 comparable to the case of 3Dv-
M dip. The waveform comparisons at stations ALE and LVZ are shown also in Fig. 9.
The variance reduction value is 56.45%. (3) The slip distribution for the case of 1Dv-
Sdip is confined to a relatively small area with elongated shape along the dip-
direction (Fig. 10). Slip directions are towards the east, which is similar to the case of
3Dv-Sdip. Maximum slip is 50 m and the moment magnitude is 8.93, smaller than the
case of 3Dv-Mdip. Two examples of waveform comparisons at stations ALE and
LVZ are shown along with the slip distribution in Fig. 10. The variance reduction
value is 41.71%.

The results of finite fault inversions for the four schemes show that the cases for
3D velocity model have much higher variance reduction values (55.18 % of 3Dv-
M dip and 56.45 % of 3Dv-Sdip) compared to those of 1D velocity model (47.51 % of
1Dv-Mdip and 41.71 % of 1Dv-Sdip). For the 3D velocity model it is not easy to
choose the better one between the 3Dv-Mdip and 3Dv-Sdip schemes, since the
difference (1.27 %) of variance reduction values between them is not significant.
However, for 1D velocity model, 1Dv-Mdip scheme of multi-dip case has
significantly higher value than that of 1Dv-Sdip scheme of single-dip case. Thus we
can conclude that the choice of 3D velocity model is generally most important, and
the choice of the multi-dip fault model is the next in finite fault waveform inversion
process for slip distribution.

4.4. Application to Tsunami Simulation
To test the applicability of the results from the finite fault modeling to tsunami simulation, the software Clawpack 5.2.0 (Clawpack_Development_Team, 2014) was used to simulate tsunami using the slip distribution obtained by finite fault inversion described in previous sections. The software calculates initial sea surface deformation due to inclined shear and tensile faults using Okada’s formulations (Okada, 1992). And it simulates propagation of tsunami waves caused by the sea surface deformation using finite volume method, with effects of seafloor bathymetry.

The tsunami waves are simulated using the fault slip distributions from the finite fault inversion of the Great 2011 Mw9.0 Tohoku-Oki earthquake. For the bathymetry effect, we used National Oceanic and Atmospheric Administration (NOAA) ETOPO1 1-minute Global Relief grid database with 4-minute grid space model. The results are compared with the observations recorded by four DART buoys located on the east coast of Honshu (Fig 11a). The four buoys are DART-21418, -21401, -21419, -21413 in the order of increasing distance from the hypocenter of the earthquake.

The computed tsunami waveforms using slip distributions from finite fault inversions using the four schemes corresponding to combinations of two velocity models and two fault geometry models are shown in Fig. 12. In the scheme of 3Dv-Mdip, the maximum height amplitudes of the simulated tsunami waves at each buoy differ in a small range of 0.06 m - 0.19 m from the observation (Fig. 11f). At the closest buoy, #21418, the simulated tsunami waveform underestimates the maximum amplitude of the observation by 0.06 m. At #21401, #21419 and #21413, the simulation underestimates the observation by 0.05 m, 0.1 m, and 0.19 m, respectively.

In the case for 1Dv-Mdip, the maximum amplitudes of simulated tsunami waves deviated from the observation in the range of 0.25 m – 0.9 m. It underestimated the amplitudes at buoy #21418 by 0.9 m, buoy #21401 by 0.25 m, #21419 by 0.22 m, and
For 3Dv-Sdip case, the simulated waves underestimated observation recorded at buoy #21418 by 0.43 m, #21401 by 0.1 m, #21419 by 0.15 m, and overestimates the observation recorded at buoy #21401 by 0.1 m. The maximum amplitudes of simulated tsunami waves for 1Dv-Sdip showed the largest deviation from the ones of observation. They underestimated the observation recorded at buoy #21418 by 1 m, #21401 by 0.31 m, #21419 by 0.28 m. However, the simulated tsunami wave at buoy #21413 fit the amplitude of the observation.

The deviation range of tsunami heights obtained from simulations using the finite fault inversion result for the scheme 3Dv-Mdip was the smallest among the four combination schemes of the velocity and fault models. Even though it was not easy to choose the best scheme in the seismic waveform inversion due to comparable variance reduction values for 3Dv-Mdip and 3Dv-Sdip cases, we found that the tsunami simulation based on the scheme 3Dv-Mdip predicts the observed tsunami in the best way. This may be due to Mdip slab model more accurately reflects the actual fault geometry than the Sdip.

5. CONCLUSIONS

We developed a new method for fast and accurate determination of a megathrust rupture process based on most up-to-date plate interface geometry model Slab1.0 and SEM for computation of synthetic Green functions in laterally heterogeneous 3-D mantle model S362ANI and 3-D crust velocity model CRUST2.0 applicable to tsunami early warning. The rapid determination of the rupture process is essential for mitigation of disasters. One of the advantages of the method presented in this study over the conventional methods is that the method does not need priori information on the focal mechanism determined by CMT, because the fault plane and corresponding
Green’s functions were already computed and stored before the earthquake. Immediately after retrieving recorded data at occurrence of a megathrust earthquake, the rupture process can be computed in a short time by least-square inversion technique using the Green’s functions. Another advantage is the multi-dip fault model and 3-D velocity model used in this method could give more accurate result than or, at least, comparable to those of conventional methods based on a single-dip fault model from the CMT information and a velocity model of 1-D or 3-D in both finite fault inversion and tsunami simulation. The inversion method presented in this study can give a solution independent of those based on CMT information.

Among the four schemes of waveform inversions corresponding to four combinations of two velocity models (3-D S362ANI and 1-D PREM) and two fault geometry models (multi-dip model based on Slab1.0 and single-dip model based on CMT solution) in the inversion for the great 2011 Mw9.0 Tohoku-Oki earthquake, the schemes utilizing 3-D velocity model show highest variance reduction values between the observed and synthetic waveforms. And the tsunami waveforms from 3-D velocity model with multi-dip fault models show the most similarity to the observations. This conclusion demonstrates that 3-D velocity model and Mdip slab scheme adequately describe the tsunami, and that this method could be applied to most of the megathrust earthquakes occurring in other subduction zones, even though the conclusion was derived from the inversion process for the great 2011 Mw9.0 Tohoku-Oki earthquake.

There are several subduction zones with megathrusts faults that can cause a large earthquake and consequently large-scale tsunamis in the world (Fig. 1). Since the multi-dip fault models based on Slab1.0 have been constructed for all the subduction zones and corresponding Green’s functions in global 3D velocity model are computed for the world-widely distributed broadband seismic stations, the rupture process can
be computed in a short time right after a large earthquake using the waveform inversion method presented in this study. The calculation time for the rupture process inversion was about 10 seconds, and one for the tsunami simulation based on the rupture process was about 10 minutes on personal laptop computer. The megathrust fault models and corresponding Green’s functions could be continuously developed and updated. Furthermore, different weights could be given to body waves and surface waves in the inversion process for slip distribution in order to control the effects of the waves on the accurate computation of the proper tsunami waves, even though the current method uses the full waveforms without the weights. The accuracy and calculation time of the tsunami wave prediction method proposed in this study are to be improved in the future.

ACKNOWLEDGEMENTS

This study was supported by the ‘Research for the Meteorological and Earthquake Observation Technology and Its Application’ project of the National Institute of Meteorological Research.
Figure Caption

**Figure 1.** Distribution of multi-dip finite fault models constructed based on subduction-zone plate interface geometry model USGS Slab 1.0. The location of the modeled finite fault for each fault segment in this study is marked by a rectangle, and an abbreviation name (Table 1) is assigned with white colored characters. The model is defined by depths, strikes and dips at locations in longitudes and latitudes at an Interval of 50-km, while Slab 1.0 defined by those at locations in longitude and latitude at an Interval of 0.1°. The depths of the Slab1.0 are represented by colored scale in km.

**Figure 2.** Comparison of observed broadband vertical component waveforms and synthetics by SEM in 1D PREM and 3D S362ANI velocity structures. The waveforms used for comparison are of the 2011 March 9 Mw 7.3 near-east-coast Honshu, Japan, earthquake (foreshock of the 2011 March 11 Mw 9.0 Tohoku-Oki, Japan earthquake). Stations of seismograms are ARU (56.06°), DGAR (79.5°) and GRFO (82.4°). The black traces are the observed seismograms, and the red traces are the synthetics computed in 1D (a) and 3D (b) structures using source parameters of GCMT solution. Larger deviations are found for the synthetics in 1D model compared to 3D model.

**Figure 3.** Locations of globally distributed seismic stations, for which the Green functions with sources at all modeled subfaults in subduction zones are calculated and stored in the database. The red squares are GSN, yellow are GEOSCOPE, black are GEOFON, and blue are MEDNET networks. Total number of stations is 177 and corresponding total number of Green's functions are 2,767,572.
Figure 4. Synthetic test of the inversion process for a slip distribution on the multi-dip finite fault model with a constant strike based on Slab1.0 in the 3D S362ANI velocity model. The fault model corresponds to the eastern Honshu segment (S4) in the KUR region (Table 1 and Fig. 1). (a) Artificially designed slip distribution (b) Inversion result of synthetic seismograms from the slip distribution in (a). The inset shows A-A’ vertical cross section of the fault with multi-dips in degree. W1~W5 indicate subfaults with numbers counting from the trench. The vertical and horizontal distances are in the same scale.

Figure 5. Global locations of stations used in the exemplary finite fault inversion for 2011 Tohoku Earthquake. The stations are located at epicentral distances 30˚ - 90˚ and have relatively uniform azimuthal coverage.

Figure 6. Result of the finite fault inversion for the 2011 Mw 9.0 Tohoku earthquake using the 3D S362ANI velocity model and the multi-dip fault model based on Slab1.0 with a constant strike (Segment S4 in KUR region). The rupture velocity of 2.5 km/s and subfault duration time of 50 s were used. The resulting Mw was 9.05, and variance reduction was 55.18 %. Slip distribution with amplitudes and directions is represented by colors and arrows on the left side of the figure. The Inset is explained in Fig. 4. Comparisons between the observation (black) and synthetic waveforms from finite fault modeling (red) are shown on two columns on the right. The signals on the first column of waveforms are the east-west, north-south and vertical component waveforms, from top to bottom, for station ALE. The waveforms on
right column are the east-west, north-south and vertical components waveforms for
station LVZ.

**Figure 7.** Comparison of two finite fault models with constant strikes in the eastern
Honshu segment. The rectangular frame of solid line in black color represents the
multi-dip finite fault model based on Slab1.0 (S4 in KUR). The other rectangular
frame with dots in orange color as subfault center points represents the single-dip
fault model based on the CMT solution of the 2011 Mw 9.0 Tohoku earthquake. The
red star is for the epicenter location of the 2011 Tohoku-Oki earthquake reported by
USGS, and the black star is for the centroid location reported by global CMT. The
inset shows the comparison of the two model’s depth profiles. The piecewise-linear
curved line in black color is for the fault plane trace of the multi-dip fault model, and
the straight line in red color is for the fault plane of the single-dip fault model. The
vertical and horizontal distances are in the same scale.

**Figure 8.** Result of the finite fault inversion for the 2011 Mw 9.0 Tohoku earthquake
using the 1D velocity model (PREM) and the multi-dip fault model based on Slab1.0
with a constant strike (Segment S4 in KUR region). The rupture velocity of 2.5 km/s
and subfault duration time of 50 s were used. The resulting Mw was 8.89, and
variance reduction was 47.51 %. Slip distribution with amplitudes and directions are
represented by colors and arrows on the left side of the figure. The Inset is explained
in Fig. 4. Comparisons between the observation (black) and synthetic waveforms
from finite fault modeling (red) are shown on two columns on the right. Descriptions
on this part of the figure are given in Fig. 6.
Figure 9. Result of the finite fault inversion for the 2011 Mw 9.0 Tohoku earthquake using the 3D velocity model (S362ANI) and the single-dip fault model based on CMT solution. The rupture velocity of 2.5 km/s and subfault duration time of 50 s were used. The resulting Mw was 9.02, and variance reduction was 56.45 %. Slip distribution with amplitudes and directions are represented by colors and arrows on the left side of the figure. The inset shows A-A’ vertical cross section of the fault with a single-dip in degree. W1~W5 indicate subfaults with numbers counting from the trench. The vertical and horizontal distances are in the same scale. Comparisons between the observation (black) and synthetic waveforms from finite fault modeling (red) are shown on two columns on the right. Descriptions on this part of the figure are given in Fig. 6.

Figure 10. Result of the finite fault inversion for the 2011 Mw 9.0 Tohoku earthquake using the 1D velocity model (PREM) and the single-dip fault model based on CMT solution. The rupture velocity of 2.5 km/s and subfault duration time of 50 s were used. The resulting Mw was 8.93, and variance reduction was 41.71 %. Slip distribution with amplitudes and directions are represented by colors and arrows on the left side of the figure. The inset is explained in Fig. 4. Comparisons between the observation (black) and synthetic waveforms from finite fault modeling (red) are shown on two columns on the right. Descriptions on this part of the figure are given in Fig. 6.

Figure 11. Results of tsunami simulations using slip distributions from finite fault inversions based on four combinations of the velocity and fault models for the 2011 Tohoku-Oki earthquake. (a) Distribution of DART buoy stations used in comparisons
of the recorded tsunami heights with simulated ones. (b)-(e) Comparisons of observed tsunami height wave forms at DART-21401, -21413, -21418 and -21419, respectively, with corresponding simulated waveforms from the four combination of models: 1D velocity and single-dip fault models (1Dv-Sdip), 1D velocity and multi-dip fault models (1Dv-Mdip), 3D velocity and single-dip fault models (3Dv-Sdip), and 3D velocity and multi-dip fault models (3Dv-Mdip). (f) Variation of the maximum amplitude difference as the observed minus the simulated ones, at the four DART buoy stations.
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