# Pure and Applied Geophysics

## Determination of megathrust rupture processes using plate-interface-based fault models and 3D Green’s functions: An application to the 2011 Mw 9.1 Tohoku earthquake

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**Abstract:**

In order to understand physical processes of megathrust earthquakes, and thus to analyze hazards of the regions, proper information of the rupture processes are essential. In this study, we develop a technique for determination of large spatial-scale rupture processes on megathrust faults in subduction zones as soon as possible, based on teleseismic broadband full-waveform inversions using realistic models of finite fault geometries and 3D global velocity structures. Finite fault geometry models are constructed for eleven subduction zones of the circum-Pacific area, utilizing the 3D plate interface model Slab 1.0 of USGS. Green’s functions for available pairs of subfaults and globally distributed stations to be used in the inversions are computed in the global 3D velocity model using spectral element method rather than in 1D velocity model. This scheme accommodates synthetic waves with lateral velocity variations especially for surface waves which is useful in estimations of large spatial-scale slip distributions. The data utilized are teleseismic broadband full-waveform records including body waves and surface waves at the epicentral distance of 30° ~ 80°. The observed data are inverted for fault rupture processes, based on the non-negative least-square technique with a multiple source time window scheme for each subfault. The applicability of the method is tested for the 2011 Mw 9.0 Tohoku-Oki earthquake, and the result shows that the proposed scheme of the finite fault inversion produces reasonable results of slip distributions.
Dear Editor:

We are submitting the revised manuscript titled “Determination of megathrust rupture processes using plate-interface-based fault models and 3D Green’s functions: An application to the 2011 Mw 9.1 Tohoku earthquake” by Baag, S.-Y, Rhie, J., Yoo, S.H., Kim, S., Kim, S.-B., and Kang, T.-S. (Manuscript # PAAG-D-18-00713) for consideration for publication in the Pure and Applied Geophysics.

The manuscript is drastically revised in several aspects, especially for contextualization of contents clarifying the purpose, logical development in methodology, relationships with other techniques, and merits & drawbacks. We thank the two anonymous reviewers for their help with valuable comments and opinions. The reviewers’ criticism and corresponding reply are attached to the end of this cover letter.

The main point of the manuscript is essentially the same as that of the previous one: developing a technique for modeling of large spatial-scale slip distributions on megathrust faults as soon as possible after occurrences of earthquakes. The application of the method was tested with 2011 Tohoku-Oki, Japan earthquake.

Our manuscript has 7 colored figures.
The supplementary materials have 1 table and 6 colored figures.

Sincerely,

Junkee Rhie and co-authors
Comments and replies

Manuscript # PAAG-D-18-00713
Manuscript title:
Determination of megathrust rupture processes using plate-interface-based fault models and 3D Green’s functions: An application to the 2011 Mw 9.1 Tohoku earthquake”
Authors: Baag, S.-Y, Rhie, J., Yoo, S.H., Kim, S., Kim, S.-B., and Kang, T.-S.

Reviewer #1:

<Comment 1>
The main lacking of the manuscript is the contextualization of this particular inversion of full waveforms versus the strategy employed in almost every other finite-fault inversion method.
This approach is dominated by the surface wave signals, which are the largest arrivals with periods longer than 50 s (the short-period end of the bandpass applied to the Green's functions), with relatively minor role for the body waves (long period S contributes) and very limited time precision (large grid size of 50 x 50 km**2, subfault source time function durations of 20 s, etc.
Source directivity information that provides precise space-time placement for short periods is on the order of up to 2 to 3 s differential times for body waves at different azimuths. There is greater variability for surface waves, and that is how this method manages to work; the directivity effect is larger for surface waves than body waves, so the relatively crude parameterization here does not lead to aberrant behavior. The consideration of tsunami predictions demonstrates that the even greater directivity sensitivity of the slowest of transient waves generated by earthquakes (tsunami waves) even better constrains the finiteness (here, showing that the default 3.5 km/s model produces artifacts when allowed to expand over large area, so one has to either lower the rupture velocity limit or a prior constrain the fault dimensions).

Reply
We agree with the reviewer’s opinion. The manuscript is drastically revised for contextualization at several places in the revised manuscript, especially by inserting the third & fourth paragraphs of Introduction. As is expressed in Abstract of the revised manuscript, the main feature of the inversion procedure given here is modeling of large spatial-scale slip distributions on megathrust faults as soon as possible after occurrences of earthquakes. Thus assumed values of parameters such as subfault size and the long period band for teleseismic waveforms are relatively large. Therefore, the full waveform amplitudes of the teleseismic waves in this frequency band are dominated by surface waves over body waves. The surface waves could be more suitable for large spatial-scale of slip distributions than that of body waves which is sensitive to smaller scales. Since the surface waves propagate earth’s shallow structures that are laterally more heterogeneous than the deeper part, we use 3D global velocity model to compute Green’s functions for the inversion. However, the inversion results lack in the information of smaller scale slip distributions. According to the reviewer’s comment, the contextualization related with this
concept of the paper is expressed in the third and fourth paragraphs of Introduction starting with characteristic features of teleseismic body & surface waves in 1D and 3D structures. The main portion of the inserted third and fourth paragraphs of Introduction in the revised version are as follows:

“~ , Theoretical Green’s functions to be used in the teleseismic waveform inversions for megathrust fault rupture distributions have been computed in global 1D layered velocity structure models. This might be partially because teleseismic body waves propagate deeper structure of the earth with laterally more homogeneity and computations with 1D models are not complicated. On the other hand, synthetic seismograms computed using 3D global layered velocity models simulate observed teleseismic data more properly, especially for long-period (50~100 s) surface waves (Tromp et al. 2008) that propagate shallower structure with laterally inhomogeneity in the earth. 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). This is in contrast with the role of body waves which is characterized by being sensitive to details of the slip distribution on the fault (Lay et al., 2010a). 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 compared with smaller effects of body waves. 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).”

“We propose a technique or procedure in the finite fault modeling for megathrust fault processes using realistic models of finite fault geometries and 3D global velocity structures. We take the main interest in large spatial-scale slip distributions rather than details of the slip distribution on the fault, and we use full-waveform of teleseismic long period (50-500 s) wave data from globally distributed broadband seismic stations. This long-period range enables us to use large or rough scales for parameters in the inversion. On the other hand, the surface wave data with relatively larger amplitudes has more important roles in the full-waveform inversion compared with the contribution of the body wave with higher-frequency contents and higher sensitivity to smaller spatial-scale slip distributions. Since The surface waves propagate earth’s shallow structures that are laterally more heterogeneous than the deeper part, we use 3D global velocity model to compute Green’s functions for the inversion. Actually, the body wave data is already available at the time of retrieving the surface wave data. Thus, we utilize teleseismic broadband full-waveform seismic records including body waves and surface waves in the inversion for the slip distribution, even if limited information from body waves would be obtained compared with that from surface waves. The additional computational time of the inversion due to the inclusion of the body wave data is negligible.”

<Comment 2>

So, given that the Green’s functions are mainly for the surface wave energy, and there is almost no discernible difference in the body wave portion of the comparison of 1D and 3D Green’s functions with data in Figure 2, it is by no means surprising that using a 3D model that improves the shallow Earth structure to allow improved fit of surface wave dispersion, will give closer agreement with the observations.

This is expected, but the issue is whether the improvement in fit in Figure 2 is so good that the remaining, substantial disagreement in timing of the surface waves is small enough that
it does not bias (blur) the finite-fault inversion when the surface wave data dominate the finite-fault inversion. In other words; yes, there are better Green's functions for the 3D model for surface waves (not evident at all for the body waves), but the errors in ARU and DGAR relative to the good fit in GRFO will project into the source, corrupting the image of the model. It is the inadequacy of surface wave Green's functions that leads to focus on the precise body wave windowing of P and SH waves that dominate most finite-fault inversions; even the method of Chen Ji, which does use surface waves as to stabilize moment determination, uses a narrow band very long period filter, so there is almost no bandwidth in the surface wave contribution.

Reply:
There is no problem in wave waveforms of body waves in 1D velocity model in Fig.2, as the reviewer pointed out. The phrase “waveforms for synthetics” may lead to misunderstanding, so the phrase is changed to “synthetic surface waveforms” in the last sentence of the first paragraph in the original version of the manuscript, as follows:

“The comparison between the observed and synthetic vertical component seismograms (Fig. 2) filtered with passband of 50~500 seconds shows that there are larger deviations of synthetic surface waveforms in 1D model compared to those in 3D model.”

With regard to travel time misfits at ARU and DGAR stations, there are the same amount of time shifts from observations for the synthetic body and surface waves in both velocity models. It is expected that there would be distortion of slip distributions caused by these time shifts of Green’s functions in the inversion. We use the mainshock data of the 2011 Tohoku earthquake in the inversion that is mainly depending on surface wave data with the time shift problem at some stations, and resulting slip distribution is similar to those from majority of previous works, as shown in Attachment Figure 1 attached to this rebuttal letter. Thus we expect that the effect of the time shift problem might not be so large.

We agree with your comment that the precise windowing of body waves is important for the finite fault inversion. On the other hand, we concentrate more on large spatial-scale slip distributions and not on the details in this paper, which is stated in the fourth paragraph of introduction of the revised version. We hope that this could be an example showing that the inversion based on mostly surface wave with both of advantage and disadvantage also produce proper slip distributions at least for a large spatial-scale.

<Comment 3>
The ‘dipping’ interface model is nothing special; most inversions nowadays at least allow for variable dip over the small number of ruptures that have such large width along dip to warrant dip change. Here the subfaults are 50 km wide, so planar segments of that width are used; and for the 2011 event the shallowest two subfaults are actually well-approximated by the constant dip model and that is where the main slip locates, so the comparisons of variable dip and uniform dip cases are not that different (Fig. S4). It is unnecessarily confusing to be also varying the strike for the constant dip models. I think the authors are trying to show the difference of the point-source model versus the plate boundary model, but that is secondary. What is more interesting is whether the 3D versus 1D matters for the planar versus curved faults; I would redo Figure S4 to have uniform strike. Many people use the strike of the trench to define the likely fault strike, not just the point-source moment tensor, as those are often unstable in their very initial solution.
Reply:

For the statement on the use of ‘dipping’ interface model, a sentence is inserted to the 5th paragraph of Introduction as follows: “Thus the fault geometry models have the varying dip type of structures which is increasingly used in finite fault inversions.” We agree with the reviewer’s opinion about the similarity between the constant and varying dip models for shallow events, and following two sentences are inserted to the second paragraph of the discussion section.

“~ . One of the possible reasons for the similarity for this Tohoku earthquake is that the shallow portions of the fault hosting the main slip distribution have similar dips in the two models of varying dip and CMT-based constant dip. Even though the use of Vdip-related pair has no advantage in the variance reduction, the ESE directions of the main slip from this pair are in accordance with the horizontal coseismic movements of GPS sites in Honshu (Simons et al., 2011; Tajima et al., 2013) in comparison with the results from the C Dip-related pairs showing E or ENE directions of slip.”

With regard to the constant dip scheme in the manuscript, we did not conceptually plan to compare the dip model based on the plate boundary geometry with the model from the point source solution. Instead, we put emphasis on the fast determination of slip distribution. Therefore, we attempted to compare the result determined using our pre-designed varying-dip fault model based on the plate boundary, with the result firstly determined using the fault model from the CMT solution after occurrence of an earthquake. Thus we would like to keep the original plan in the manuscript, even if there may be a little confusion as the reviewer point out.

<Comment 4>

The back-projections for 2011 showed very early on that rupture velocity was low early in the rupture and likely increased with low moment release later in the rupture. The use of constant Vr or overly constrained finite extent is a challenge for all inversions; my impression is that even with the 3D Green's functions and use of surface wave energy, the data cannot really independently resolve the placement of slip, so there is no real improvement in that resolution. It is why many have looked to joint analysis with tsunami waves to solve this problem.

Reply:

The multiple source time window scheme used in this study was designed to afford the possible low rupture expansion velocity at the beginning stage of the rupture process. We use the reference (i.e., maximum) rupture velocity of 3.5 km/s and 10 time windows of 20-s duration each at 10-s time interval in multiple source time window scheme. Thus, at a 50-km distance from the hypocenter, the minimum possible rupture velocity is allowed to be down to 0.5 km/s (Figure 6 of the text). The minimum rupture velocity is further reduced at shorter distances from the hypocenter, such as 0.2 km/s. In Figure 6, most of rupture within 60 km from the hypocenter occurred with the rupture expansion speed of 0.3 – 1.2 km/s, except for 3.5 km/s. On the other hand, overly constrained finite extent in the inversion may not plausible, as the reviewer pointed out. In general sense, we agree with the reviewer’s opinion that even
with the 3D Green's functions and use of surface wave energy, the data cannot really independently resolve the placement of slip. One sentence was already given as the last sentence to the last paragraph in Discussion in the old and new versions: “In order to refine the fault slip distribution model, the inversion scheme may need to be constrained by geodetic and/or tsunami data.

**Minor editing comment**

The paper is generally very well-written. Minor editing is needed (e.g., line 4 of Intro: 'Mw 9.3 occurred', would be better as 'Mw 9.3 which occurred', line 1 of 3rd Paragraph of Intro 'researches' would be better at 'research'. etc.

**Reply:**
Mistakes are corrected in the revised version. The line 1 of the 3rd paragraph in the old version of manuscript is repositioned to the line 1 of the 2nd paragraph in the revised version, in the process of merging the two short paragraphs into one.

**Overall opinions**

**Opinion 1**
Overall, the paper is not high-impact, but is solid contribution, and could be made more impactful by better recognition of what it offers. It is not compelling to simply show that 3D Green's functions fit complete waveforms better without discussing what is better fit and what is not. The reality is that there is probably no significant impact on the body wave part of the broadband waveforms; likely there is minor improvement on long-period S, SS energy, but with the coarse time resolution of the large subfaults and long subfault source time functions, this is almost certainly insignificant for the finite-fault inversions.

**Reply:**
These points are reflected in the third & fourth paragraphs of Introduction in the revised version.

**Opinion 2**
Whether the 3D model has any impact on the near-source velocity structure is not addressed, but the model, even with the 3D crust, is so coarse and will not represent slab structure and wedge structure in any detail, so there is unlikely any gain to be had using '3D' structure in the source region when it is so poorly represented.

**Reply**
We agree with the opinion and insert a sentence at the end of the first paragraph of Section 2.2 as follows:
“One other hand, the 3D crust and upper velocity model used in the paper has broad lateral variation, and thus it may not sufficiently represent details of local source structures such as the slab and wedge structures in subduction zones.”

**Opinion 3**
An additional limitation of the SEM code is that it does not account for water reverberations, so while there can be some influence of bathymetry variation in the body wave portion of the calculation, it is incomplete and water multiples are missing. This is not a big deal when you filter out almost all of the P wave with a 50 s low pass filter, but there is no discussion here of the strengths and limitations of the code and the 3D model that is used.

**Reply**
Following sentences are added to the end of the second paragraph of Section 2.2:
“The SEM code does not account for the sea water reverberations influenced by bathymetry variation in the P wave portion of the synthetics, and thus the water multiples are missing in computed seismograms. However, the phase does not need to be modeled, because such a high frequency multiples are smeared out in the data processing by the 50-s low pass filter.”

**Opinion 4**
In general, first-order solutions based on the progress in predicting surface wave propagation are achieved here. Maybe that is helpful for rapid solutions, although there is no real problem with current rapid solutions demonstrated here(?) . I think it would be misleading to think, or claim as is done here, that because the phase corrections from 3D are helping to reduce the variance in overall waveform fit, that the slip model is any better resolved than by methods that emphasize discrete body waves that do not suffer from such 3D Green's function limitations.

**Reply:**
We agree with the opinion. Thus descriptions on the purpose of the paper limited to relatively fast determinations of large spatial-scale slip distributions and advantages/disadvantages of the technique are given in Introduction by inserting two paragraphs (the third and fourth) of explanations in the revised version. According to the reviewer’s comment, we corrected all sentences in the manuscript that could be misleading to the incorrect concept that the slip model is any better resolved than those by methods that emphasize discrete body waves.

**Reviewer #2**
Reviewer #2: Review of « Determination of megathrust rupture processes using plate-interface-based fault models and 3D Green's functions: An application to the 2011 Mw 9.1 Tohoku earthquake » submitted at Pure and Applied Geophysics by So-Young Baag, Junkee Rhie, Seung-Hoon Yoo, Seongryong Kim, Sat-Byul Kim, and Tae-Seob Kang
Baag et al. present an approach to invert teleseismic broadband data to image the slip distribution of large subduction earthquakes using and 3D Green's functions. They discretize global subduction faults given by the slab1.0 model into 2606 subfaults and calculate 3D Green's functions relating each of them to 177 stations distributed world-wide. They show an example of the difference between currently used 1D Green's functions and 3D Green's functions for the March 9 2011 Mw7.3 earthquake (a foreshock of the Mw9.0 Tohoku-Oki earthquake). They then perform a slip inversion of the 2011 Mw9.0 Tohoku-Oki earthquake using 3D Green's functions and discuss their results, in particular the impact of the 3D Green's functions and different fault geometries as well the agreement with tsunami observations.

<Comment 1>

Overall the manuscript is fairly clear and well written but it is not clear to me what the angle of the study is. Some changes in the structure of the article might help highlight the main points the authors want to make and clarify its addition to the state of the art.

Reply

We agree with the comment for the original version. The primary purpose of the paper is to obtain large spatial-scale slip distributions as soon as possible after occurrences of megathrust earthquakes in subductions zones. However, the purpose is not directly related to the early warning of seismic or tsunami hazards. Words and sentences are inserted in Abstract, Introduction, Discussion, and Conclusion in the revised version as follows:

(i) In Abstract:
Words “accurate and detailed” are erased in the first sentence, because they may be confused with the purpose of the paper. In the second sentence, “large spatial-scale” and “as soon as possible” were inserted, conforming to the purpose.

(ii) In Introduction:
Most of the third and fourth paragraphs of Introduction are new. The second sentence of the fourth paragraph reads “We take the main interest in large spatial-scale slip distributions rather than details of the slip distribution on the fault, and we use full-waveform of teleseismic long period (50-500 s) wave data from globally distributed broadband seismic stations.” The last sentence of the sixth paragraph revised to “Including times for data acquisition, preprocessing and the inversion, the slip distribution could be obtained in a few hours depending on the data quality and the azimuthal distribution of stations. Thus the purpose is not directly related to early warning of hazards.”

(iii) The last sentence of Conclusion:
“Since the purpose of the research is not directly related to the early warning of seismic or tsunami hazards, we do not attempt to develop an automatized device for all the inversion process at this time.”
<Comment 2>

Is the main point of the study about fast (automatic?) finite-fault slip inversion? In that case, I would suggest discussing in detail the advantages and differences of the proposed approach with regards to existing approaches (e.g. Hayes, 2011, Crowell et al., 2012, Ohta et al., 2012, Melgar et al., 2013, 2015, USGS... and many more), if and how it could be used for tsunami warning. The authors computed all these Green's functions, but are not really doing anything with them later on in the study. Is that for future use for rapid slip inversion? Will it be available for everybody?

Reply:
The main point of the study is fast finite-fault slip inversion. We are hoping that the proposed method would contribute to preliminary determination of rupture processes of megathrust earthquakes. While the purpose of the research is not directly related to the early warning of seismic or tsunami hazards, we think that it may be an interesting try to develop an automatized device for the inversion process, with some significant improvements (i.e. accuracy and resolution) to the currently proposed method. The Green’s functions are to be used in the future. While it might not be an open-source, it will be available upon request.

<Comment 3>

Is the main point about how using 3D Green's functions may help improve finite-fault slip inversions? In that case, some more material might be needed.

Reply

The main purpose of the inversion procedure given here is modeling of large spatial-scale slip distributions on megathrust faults as soon as possible after occurrences of earthquakes. Thus assumed values of parameters such as subfault size of 50 km and the long period band of 50-100 s for teleseismic waveforms are relatively large. In this frequency band, the full waveform amplitudes of the teleseismic waves are dominated by surface waves over body waves especially P waves. In addition, the use of surface waves is more appropriate in inversion for large spatial-scale of slip distributions than that of body waves which is sensitive to smaller scales. Since the surface waves propagate earth’s shallow structures that are laterally more heterogeneous than the deeper part, we use 3D global velocity model to compute Green’s functions for the inversion. These points are explained in Abstract and the third & fourth paragraphs of Introduction in the revised version of the manuscript. Even though we did not deal with detailed study of statistical analysis for the 1D and 3D velocity models for this paper, we plan to continue the research in the near future in order to utilize the results in the finite fault inversions.

<Comment 4>
<4-1>
The comparison of 1D and 3D synthetics for the Tohoku earthquake is a good start but 1 example is hardly enough to make a case. A systematic comparison for all the computed Green’s functions might be one way to strengthen this axis (some statistics on the 2 sets of Green’s functions, RMS of their differences...).

Reply
We understand the suggestion is good for completeness of proof for the Green’s functions. However, it is a big task to do a statistical analysis for the enormous number (2,767,572) of Green’s functions, which would be hard to be done in a limited time of the revising period of the manuscript. We hope that the suggested process could be done in the future. For this paper at this time, it is assumed that the 3D Green’s functions computed using the SEM software would be correct and could be used in the inversion. Instead, we tried to perform tests for the Green’s functions selecting one subfault from the currently-tested fault segment. We selected the subfault that is located in the middle of the KUR04 segment, which is L08W03. For calculated Z-component seismograms of 1D and 3D Green’s functions at all stations, the waveforms are cross-correlated between the 1D and 3D Green’s functions and aligned in time. And we obtained the variance reduction values of the aligned waveforms. The results are as shown in Attachment Figure 2 and explained below.

Overall, the variance reduction values are within 65~100 % range with the maximum at 82 %, and has a few outliers in 40%~55% (Attachment Fig 2a). The values show fluctuating pattern with respect to azimuth (Attachment Fig 2b) and the pattern is the same for each distance ranges. For all distances, the values above 70 % appear in the azimuthal ranges about 0° ~ 50°, 160° ~230°, and about 300° ~ 350°. In azimuthal ranges 50° ~ 160°, and 230° ~ 300°, the variance values are relatively lower. The time difference was calculated via cross-correlation. The time difference between 1D and 3D Green’s functions (plus value for delayed 1D case) are mostly in the range of -28 s to 16 s with peak frequency at 8 s – 10 s in an asymmetric shape of distribution (Attachment Fig 2c). There are a couple of outliers at the value near -30 s and at the range 26 s – 30 s (Attachment Figure 1c).

The 1D Green’s functions show the tendency to lag behind 3D ones in the azimuthal ranges of 0° ~ 50° (with a few exceptions depending on distance range) and 180° ~ 300° s (Attachment Figure 2d). In azimuthal ranges 50° ~ 180° and 300° ~ 350°, it tends to lead 3D waves. This is not surprising, since the 1D model is isotropic, while 3D model is takes anisotropy into account.

<4-2>
On the inversion procedure itself, a better variance reduction does not guarantee that the model is better. The accuracy of a finite-fault inversion is very hard to evaluate. How slight errors in the 3D model would affect the result of the inversion? The resolution of teleseismic data is known to be poor. I am impressed by the consistency of the inverted models. Could you show resolution (checker board) tests?

Reply
We agree with the opinion that a better variance reduction does not guarantee the better model, and feel difficult to answer the question about the effect of the slight error in 3D model on the result of the inversion.

One of the purposes of the inversion in this paper is to obtain smooth variation of slip distribution in large spatial scale. Thus the checker board test for alternating slip distribution is not in accordance with the purpose. However, we tried to do the test and the result is shown in the attachment Figure 3 and explained as follows:
The checkerboard testing was done with single-time window inversion, since its purpose is to check the resolution of spatial rupture distribution rather than the one of temporal change in rupture process. The results are produced for the simultaneous rupture, and rupture duration time of 50 s. The testing was done with two different scheme of patch sizes—The first scheme is composed of 50 km x 50 km patches of the subfault size with no smoothing operation in the inversion, and the second scheme is composed of 150 km x 150 km patches and 150 km x 100 km patches with twenty percent of smoothing operation in the inversion. Both schemes are designed to have alternating slip patches of 10 m and 5 m. The figures on the left show the input rupture distribution that checkerboard test is meant to reproduce, and the right show the inversion results. The results show relatively lower resolution in the scheme of smaller patch size of 50 km x 50 km, but higher resolution in the scheme of larger size of patches of 150 km x 150 km.

<Comment 5>

I am also surprised by the tsunami data fit (Fig. 7). The fault model does not reach the trench (Fig. S3). Therefore, we should observe a significant delay corresponding to the travel time of the tsunami between the edge of the fault model and the trench. The only way to fit the first arrival of the tsunami wave on the DART buoys is to put slip at the trench. This is actually how we know that the slip did reach the surface (at the trench). There is clearly something wrong with the tsunami prediction V3.5N75.

Reply

The main slip distribution is confined within the rectangular region depicted by the straight red lines in Figure 7. There are significant slip distributions near the NE and SE corners inside of the region (Figure 4). The tsunami wave from the NE portion of these slips become the first arrivals at the NE stations (DART#21418, 21401 and 21419), and the wave from the SE portion become the first arrival at the SE station (DART#21413). Therefore, the tsunami wave from the area of stronger slips at the center position between the two NE & SE corners does not become the first arrival at any of the DART stations. Even the wave from the possible slip in the near-trench area between the trench and the fault edge does not become the first arrival at stations. Thus the exact arrival times of these signals of the phase are not easy to be identified in the plot of traces. However, the qualitative inspection of the changed shape of the tsunami trace could be utilized for the checking for the surface reaching of the slip, using the technique suggested by the reviewer.

We agree with the reviewer’s opinion that there is something wrong with the tsunami prediction V3.5N75. It is discussed in the tsunami section of Discussion in the original and revised versions.
Minor comments

(1) Page 4 L 40-52 : Consider rephrasing

(2) L54 : Usually --> often
   Reply: It is corrected in the third sentence of the second paragraph in Introduction in the revised version.

(3) Page 9 L17 : 100 km seems deep
   Reply: For the phrase “up to 100 km” in the first sentence of the last paragraph in section 2.1, this upper limit may be unnecessarily deep, but it is for a few cases of subduction zones.

(4) 2.2 What source model did you use (length, width, amount of slip)? Did you use a source model you inverted for using 3D Green's functions? If you invert for these parameters using 1D GFs and plot the 1D and 3D synthetics, does the 3D synthetics still fit best the observations?
   Reply: The source model used in computation of synthetics for the foreshock is not a finite fault model obtained from a finite fault inversion process, but is a point source model from the CMT solution with the centroid location and seismic moment components. This information is given to the revised version as the third sentence of the first paragraph in section 2.2, since it is missing in the original version.

(5) Page 10 L2 : this seems very low frequency. Could you develop on what made you use this frequency range?
   Reply: The frequency band range is from a rough empirical approximation applicable to broad spatial variations of slip distribution, avoiding complexity of waveforms. The band is to be used in the inversion scheme, but could be changed to higher frequency one depending on the purpose. (The sentence related to the comment: the second sentence from the last one in the first paragraph of section 2.2 in the revised version)

(6) Page 12 L20 : I don’t understand where the term (k-1)*delta^{twin} comes from. Could you develop?
   Reply: In multiple source time window scheme, a subfault rupture time function is described as a linear combination of weighted triangular source time functions separated by multiples of a time interval delta^{twin}. Thus k=1 is for the first triangular source time function with no time delay within the subfault time function. k=2 is for the next triangular time function with time delay of delta^{twin}. k=3 is for the third triangular time function with time delay of 2*delta^{twin}, etc. In order to help readers, the first paragraph of section 3.1 is reformed by inserting a few sentences and changing the order of descriptions.
(7) Page 13 L16: So 2 lambda_s and 2 lambda_d? If so change eq 2. Also, why is the regularization done separately?
   Reply: Since Green’s functions for rakes 45 and 135 are different, they are explicitly presented in the equation (2). On the other hand, the regularization schemes for the two rakes are the same, so they are represented by a single symbol implicitly implying the two cases rather than repeating the two in the equation. The sentence is added as the seventh sentence in the second paragraph of section 3.1 in the revised version to clarify this: “The symbols L and I implicitly contain two identical Laplacian and Identity operators, respectively, for the two rake components.” The reason why the regularization is done separately is that the slip displacement (or associated moment) on the fault has the vector property with the amplitude and direction. Its components corresponding to the two rake components are need to be independent. The formulation could be a little more complicated if you regularize the amplitudes and directions.

(8) Page 14 L39: is it moved on the center of the subfault or can it be anywhere on the fault (would be preferable)?
   Reply: The epicenter is not moved. So it can be anywhere on the fault. (Related sentence in the revised manuscript: The third sentence of the first paragraph in section 3.2 in the revised manuscript)

(9) L60: references
   Reply: The percentage was counted in this research, and recently it was renewed to be 88% of events with rupture velocity less than 3.5 km/s. A table (Table S1) listing the information on the rupture velocities of events is given with references in the supplements. This can be done using SRCMOD which is referenced in the manuscript. (Related sentence: the fifth and sixth sentences in section 3.2 in the revised manuscript)

(10) Page 16 L34: I’m not sure this is true. Actually, the different published models are fairly different from one another. Could you make a figure (maybe in the supplements) to visually compare your model with different published models?
   Reply: The second sentence of the third paragraph in section 4 in revised version is changed to “The general location and trend of major slip distribution is similar to the majority of studies done in the earthquake (Hayes et al. (2011), Lee et al. (2011), Suzuki et al. (2011), Koketsu et al. (2011), Bletery et al. (2014)), but the shapes of the distributions from most of the studies including ours are different from one another. A figure for comparison of slip distribution with those of previous researches is presented as an attachment to this reply letter (Attachment Fig 1). The figure could be included in the figure set of the supplements, but we would like to avoid the cumbersome procedure of obtaining permissions from authors.

(11) Fig 3: What is the slip patch at the South of the rupture? (absent in the snapshots and in the inversions in the supplements) Could it be related to the large aftershock in this area? How long are the time series you are inverting for?
   Reply: The isolated slip patch at the south is interpreted to be a last slip occurring at the ending time of the earthquake (about 3.5 minutes after the hypocenter time). It is unclear that it could be classified as one of the aftershocks. However, it is not a reported Mw 7.9 aftershock occurred at 28 minutes after the hypocenter time of the mainshock.
(12) If 3D Green's functions are central to your study, figure S4c should be in the main text rather than in the supplements.

Reply: One of the purpose of the manuscript is to determine large spatial-scale slip distributions using full waveform 3D Green's functions which include surface waves propagating shallower structures. In this sense, it may be plausible to move Fig. S4c for 1D case to the main text to compare with the 3D case. However, we wanted to compare and explain all the four cases including the two dip schemes at once in Fig. S4 in order not to repeat some portions of the explanation.

References:
Attachment Fig 1 Comparison of slip distributions from various studies for the 2011 Mw 9.0 Tohoku earthquake (For comment #2 of Reviewer 1, and minor comment #10 of Reviewer 2).

Attachment Fig 2. The statistical analysis for vertical components of Green’s functions in 1D and 3D velocity models (For comment #4-1 of Reviewer 2). The source subfault is located at the center of the KUR04 fault segment (L08W03), and total 102 globally distributed broadband stations are used in the statistics. The positive travel time difference indicates delay of the wave in 1D velocity model compared to that in 3D model.
Attachment Fig 3. Results of the checkerboard test (For comment #4-2 of Reviewer 2). The figures on the left ((a) and (c)) are the input rupture distribution, and the figures on the right ((b) and (d)) are the corresponding results. The input rupture distributions have alternating slips of 10 m and 5 m.
Determination of megathrust rupture processes using plate-interface-based fault models and 3D Green’s functions: An application to the 2011 Mw 9.1 Tohoku earthquake

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Key words: finite fault, teleseismic, megathrust, waveform inversion
Abstract

In order to understand physical processes of megathrust earthquakes, and thus to analyze hazards of the regions, proper information of the rupture processes are essential. In this study, we develop a technique for determination of large spatial-scale rupture processes on megathrust faults in subduction zones as soon as possible, based on teleseismic broadband full-waveform inversions using realistic models of finite fault geometries and 3D global velocity structures. Finite fault geometry models are constructed for eleven subduction zones of the circum-Pacific area, utilizing the 3D plate interface model Slab 1.0 of USGS rather than using information from CMT solutions. Green’s functions for available pairs of subfaults and globally distributed stations to be used in the inversions are computed in the global 3D velocity model using spectral element method rather than in 1D velocity model to increase the accuracy. This scheme accommodates synthetic waves with lateral velocity variations especially for surface waves which is useful in estimations of large spatial-scale slip distributions. The data utilized are teleseismic broadband full-waveform records including body waves and surface waves at the epicentral distance of 30º ~ 80º. The observed data are inverted for fault rupture processes, based on the non-negative least-square technique with a multiple source time window scheme for each subfault. The applicability of the method is tested for the 2011 Mw 9.0 Tohoku-Oki earthquake, and the result shows that the proposed scheme of the finite fault inversion produces reasonable results of slip distributions.
1. INTRODUCTION

Megathrust earthquakes in subduction zones of the circum-Pacific and Indian oceans usually devastate large areas near and far from the source region by shaking and tsunami flooding. Recent examples are the Great Sumatra-Andaman earthquake of Mw 9.3 which 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 (Ammon et al. 2005, Lay et al. 2005, Simons et al. 2011, Tajima et al. 2012). In order to mitigate such disasters, it is necessary to obtain information about the character of the earthquake source including the rupture process on the megathrust fault. (The first and the second paragraphs are merged in to one) Traditionally, values of source parameters, such as the centroid, fault orientation and seismic moment, can be obtained from a centroid moment tensor solution within 8~15 minutes after a large earthquake (Whitmore 2009). However, it is important to characterize the earthquake source as a realistic finite fault with a slip distribution rather than as a point source type (Hartzell and Heaton 1983, Hayes 2011, Lay et al. 2010).

Up to now numerous results of research (Ammon et al. 2006, Ammon et al. 2011, Bletery et al. 2014, Hayes 2011, Koketsu et al. 2011, Lee et al. 2011, Rhie et al. 2007, Shao et al. 2011, Simons et al. 2011, Suzuki et al. 2011, Yoshida et al. 2011, Yoshimoto and Yamanaka 2014, Yue and Lay 2013) have been reported on finite fault modeling for megathrust fault rupture processes of large earthquakes in subduction zones. Most of them are based on inversions of global and/or regional seismic waveforms with or without constraints of geodetic and tsunami data. Often the fault geometries and orientations as a priori information required in the inversions for slip distributions are designed as a single plane, based on information of centroid moment tensor solutions, even though other cases are increasing. Such geometries sometimes
give unreasonable results of inversions (Hayes 2011) and thus more realistic or physically-based fault plane geometries are needed to be designed before inversions (Bletery et al. 2014, Hayes 2011, Simons et al. 2011). (Next sentences in this paragraph are merged into a new paragraph as follows)

Theoretical Green’s functions to be used in the teleseismic waveform inversions for megathrust fault rupture distributions have been computed in global 1D layered velocity structure models. This might be partially because teleseismic body waves propagate deeper structure of the earth with laterally more homogeneity and computations with 1D models are not complicated. On the other hand, synthetic seismograms computed using 3D global layered velocity models simulate observed teleseismic data more properly, especially for long-period (50~100 s) surface waves (Tromp et al. 2008) that propagate shallower structure with laterally inhomogeneity in the earth. 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). This is in contrast with the role of body waves which is characterized by being sensitive to details of the slip distribution on the fault (Lay et al., 2010a). 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 compared with smaller effects of body waves. 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).

We propose a technique or procedure in the finite fault modeling for megathrust fault processes using realistic models of finite fault geometries and 3D global velocity
structures. We take the main interest in large spatial-scale slip distributions rather than details of the slip distribution on the fault, and we use full-waveform of teleseismic long period (50-500 s) wave data from globally distributed broadband seismic stations. This long-period range enables us to use large or rough scales for parameters in the inversion. On the other hand, the surface wave data with relatively larger amplitudes has more important roles in the full-waveform inversion compared with the contribution of the body wave with higher-frequency contents and higher sensitivity to smaller spatial-scale slip distributions. Since The surface waves propagate earth’s shallow structures that are laterally more heterogeneous than the deeper part, we use 3D global velocity model to compute Green’s functions for the inversion. Actually, the body wave data is already available at the time of retrieving the surface wave data. Thus, we utilize teleseismic broadband full-waveform seismic records including body waves and surface waves in the inversion for the slip distribution, even if limited information from body waves would be obtained compared with that from surface waves. The additional computational time of the inversion due to the inclusion of the body wave data is negligible. (The next paragraph starts with the second sentence of the fourth paragraph of the old version)

Finite fault geometry models are constructed for widely distributed eleven subduction zones of the circum-Pacific area, utilizing the 3D plate interface model Slab 1.0 of USGS (Hayes et al. 2012). Thus the fault geometry models have the varying dip type of structures which is increasingly used in finite fault inversions. Green’s functions to be used in the inversions are computed in 3D velocity model, S362ANI (Kustowski et al. 2008) using spectral element method (SEM; Tromp et al. 2008). Once finite fault geometries with subfault distributions are determined, a Green’s function database for source-station pairs of all the subfaults in the designed megathrust fault models and
hundreds of globally distributed broadband seismic stations is stored so as to be used readily at occurrences of large megathrust earthquakes. (This paragraph is merged to the next paragraph) We used teleseismic broadband full-waveforms including body waves and surface waves at the epicentral distance of 30°~80°. The observed teleseismic full waveforms are inverted for fault rupture processes, based on the non-negative least-square technique with a multiple source time window scheme (Olson and Apsel 1982, Hartzell and Heaton 1983) for each subfault.

As for the recent large Tohoku earthquake of Mw 9.0, the earliest estimate of the slip distribution using seismic data was provided at approximately 1.75 hours after the earthquake origin time by the US Geological Survey (USGS) National Earthquake Information Center (NEIC) (Wei et al. 2014). This was an automated estimation of the finite fault slip distribution in a 1D-velocity model based on Ji et al. (2002) using teleseismic body and surface waves, and a planar fault orientation from the USGS NEIC W-phase CMT solution (Duputel et al. 2011). Then a preliminary result was announced at 7 hours after the origin time with a revised rupture velocity and a strike direction based on the Slab1.0 plate interface model at subduction zones (Wei et al. 2014). An updated solution was released 3 days after the earthquake, with adjusted fault dip and depth of the fault top based on the Slab1.0 model, and the updated USGS hypocentral depth (Hayes, 2011). With a similar purpose, we attempt to present a procedure to invert teleseismic waveforms for large spatial-scale slip processes of megathrust earthquakes in relatively short time, utilizing the database of teleseismic Green’s functions computed and stored using pre-designed varying dip fault planes and a 3D global velocity model. Including times for data acquisition, preprocessing and the inversion, the slip distribution could be obtained in a few hours depending on the data quality and
the azimuthal distribution of stations. Thus the purpose is not directly related to early warning of hazards.

The applicability of the method is tested for the 2011 Mw 9.0 Tohoku-Oki earthquake, and the result shows that the scheme of 3D velocity model and the fault geometry model based on the Slab1.0 produces reasonable results of slip distributions. Even though the method is formulated for the teleseismic waveform inversion, it could be extended to cases of multi-type data including tsunami data and/or geodetic near-source displacements recorded by GPS with proper relative weighting between data sets at the expense of processing time for data acquisition and computations. In order to overcome the lower contribution of body waves to the inversion due to the use of full waveforms filtered in low-frequency band, the method could be extended to a joint inversion based on separate inversions for the body waves and surface waves.

2. MEGATHRUST FAULT MODELS AND GREEN’S FUNCTIONS

2.1. Construction of Megathrust Fault Models

We constructed large-scale fault geometry models of global megathrust regions to determine spatio-temporal rupture processes of large magnitude earthquakes. By using information from the USGS Slab 1.0 model, a three-dimensional numerical model of global subduction geometries (Hayes et al. 2012), we simplify the fault geometry for megathrust regions to quickly and efficiently calculate our models while still constraining a reliable result. The global subduction zones in Slab 1.0 are composed of 13 regions and we chose 11 regions to constrain 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 divided each region into multiple fault segments with different lengths ranging 400~800 km based on the curvatures of the trench e.g., only 5 segments are needed to define the Mexican subduction zone (S01, S02, S03, S04 and S05) (Fig. 1). The fault model of each segment consists of subfaults with the same strike but with varying dips. For the inversion process of slip distributions, the subfault size of the megathrust faults can vary from a smaller size of 15 km x 15 km to a larger size of 100 km x 50 km, depending on the magnitude of the earthquake (Ammon et al. 2011, Tang et al. 2012). In this study, the size of the subfault is defined as 50 km x 50 km, due to the large magnitudes of the megathrust-fault events. This size corresponds to an approximate rupture area of Mw 7.0 earthquake according to the scaling relationship of Goda et al. (2018) for the fault area and moment magnitude of tsunamigenic earthquake, which was based on Finite-Source Rupture Model (SRCMOD) Database (Mai and Thingbaijam 2014). Thus if we assume that the minimum number of subfaults is nine for proper description of spatial slip variation for a megathrust earthquake, the corresponding minimum moment magnitude is 8.1 according to the scaling relationship. Even though we define the subfault size as 50 km x 50 km, it could be changed to a desired size depending on the purpose.

To construct the fault geometry of a region, first the locations of data points corresponding to the intersection between the fault surface and the sea floor along a trench are extracted from the Slab 1.0 model. The extracted location points of the curved trench line are approximated to a piecewise linear trace with lengths of 400~800
km (e.g., S01, S02 in Fig 1.) that are smaller in the case of large curvature with subfaults in the linear trace defined every 50 km. In order to simplify the constructed fault model, the average depth along the trench is used as the depth of the intersection line between the seafloor and the surface of the fault segment. Then to derive the coordinates of the fault segment along the dip direction, coordinates of the plate interface points from Slab1.0 associated with the fault segment are projected to a 2-D vertical plane perpendicular to the trench direction (i.e., 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 approximation and piecewise linear interpolation. These line segments of 50 km correspond to the defined subfaults with varying dip directions defined by their slope.

The resulting faults have the maximum depth values up to 100 km, which sufficiently models megathrust faults from shallow, near-trench region of tsunami-generating domain to 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 March 9 Mw 7.3 near-east-coast Honshu, Japan, earthquake (A foreshock of the 2011 Mar 11 Mw 9.0 Tohoku-Oki, Japan earthquake) (Fig. 2). The source model used
for the synthetics is a point source model from the CMT solution. 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 larger deviations of synthetic surface waveforms in 1D model compared to those in 3D model. On the other hand, the 3D crust and upper velocity model used in the paper has broad lateral variation, and thus it may not sufficiently represent details of local near-source structures such as the slab and wedge structures in subduction zones.

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 two reference 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 source time function corresponding to a time window in the multiple time window scheme. The shape of the source time function is an isosceles triangle with duration of 20 s in this study, and the covered area by the function in time domain is a non-dimensional unity. The results are filtered by a pass-band of 50\textendash{}500 seconds in order to remove high frequency and very low frequency signals, and then are downsampled to a time interval such as 10 seconds (Hereafter, we call it simply Green’s functions). The SEM code does not account for the sea water reverberations influenced by bathymetry variation in the P wave portion of the synthetics, and thus the water multiples are missing in computed seismograms. However, the phase does not need to be modeled, because such high-frequency multiples are smeared out in the data processing by the 50-s low pass filter.

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. 3a). 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 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

\[ u_i(t) = \sum_{j=1}^{N_i} \sum_{k=1}^{N_k} \left[ M_{jk}^{(r45)} G_{ij}^{(r45)}(t - t_{jk}) + M_{jk}^{(R135)} G_{ij}^{(R135)}(t - t_{jk}) \right] \]

(1)

where \( t_{jk} = t_{j\text{rup}}^r + (k - 1)\Delta t_{\text{win}} \). Here, \( u_i(t) \) is the \( i \)’th component amplitude of the three-component displacement seismograms with \( N_t \) time points. Indices \( j \) represent sequential numbers assigned to subfaults for identifications with \( j = N_j \), corresponding to the total number of subfaults. Functions \( G_{ij}^{(r45)}(t) \) and \( G_{ij}^{(R135)}(t) \) are \( i \)’th component amplitudes of the Green’s functions for the \( j \)’th subfault with reference slip rake directions 45˚ and 135˚, respectively. These Green’s functions have the isosceles triangular source time function with a duration of 20 s and a unit seismic moment of \( 1 \times 10^{20} \) dyne∙cm as defined above (section 2.2). In the multiple time window scheme (Olson and Apsel 1982, Hartzell and Heaton 1983), the subfault rupture time function is described as a linear combination of weighted triangular source time functions with a specified duration and delayed by regular time differences, i.e, time windows. Thus, functions \( G_{ij}^{(r45)}(t - t_{jk}) \) and \( G_{ij}^{(R135)}(t - t_{jk}) \) are Green’s functions corresponding to the triangular source time functions delayed by \( t_{jk} \) which is the sum of source time delays corresponding to two types. The first delay comes from the time \( (t_{j\text{rup}}^r) \) of rupture propagation from the hypocenter to the center of the \( j \)’th subfault with a reference rupture velocity, and the second one is an additional time delay \( ((k - 1)\Delta t_{\text{win}}) \) for the \( k \)’th time window in the multiple time window scheme where \( \Delta t_{\text{win}} \) is the time interval between time windows. For the rupture propagation delay, we use an assumed upper limit of rupture velocity as a reference for computational convenience instead of using an infinity value. A proper value of the upper limit of the rupture velocity could be determined, based on information from results of previous
works on modeling of megathrust earthquakes in worldwide subduction zones and
additional information from SRCMOD website (Mai 2012). The value could be
modified in the process of the inversion, if necessary. Parameters $M_{jk}^{(r45)}$ and $M_{jk}^{(r135)}$
are seismic moment components in reference rake directions $45^\circ$ and $135^\circ$, respectively,
for $k$’th source time window of $j$’th subfault in the multiple time window scheme. These
moment components can be presented in terms of the unit seismic moment. Total
number of the time window for each subfault source time function is $N_k$.

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 $d$, and regularization conditions for minimum moment components and Laplace
smoothness are attached to stabilize the inversion numerically, such that

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

(2)

Here, $G^{(r45)}$ and $G^{(r135)}$ are matrices composed of Green’s function elements
$G_{ij}^{(r45)}(t - t_{jk})$ and $G_{ij}^{(r135)}(t - t_{jk})$, respectively, with dimension $(3N_s \cdot N_t) \times (2N_j \cdot N_k)$. The factors 3 and 2 in the matrix dimension are for 3 components of seismograms
and for the two reference rake directions, respectively, and the parameter $N_t$ represents
the total number of stations. $M^{(r45)}$ and $M^{(r135)}$ are column matrices composed of
elements $M_{jk}^{(r45)}$ and $M_{jk}^{(r135)}$, respectively, with the length $(N_j \cdot N_k)$ each. The column
matrix $d$ is for the observed data time series with dimension of $(3N_s \cdot N_t)$. $L$ and $I$
represent matrices containing the Laplacian operator for roughness regularization and
an identity matrix, respectively, and $\lambda_s$ and $\lambda_d$ represent coefficients for smoothing and
damping, respectively. The symbols $L$ and $I$ implicitly contain two identical Laplacian
and Identity, respectively, operators for the two rake components. 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 $M_{jk}^{(r45)}$
and $M_{jk}^{(r135)}$, respectively, are summed for total number of time windows $N_k$ and
divided by $\mu A_{sub}$ to get the slip component $s_j^{(r45)}$ and $s_j^{(r135)}$, where $\mu$ and $A_{sub}$
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

$$V_R = \left[ 1 - \frac{\sum [data(t_i) - synth(t_i)]^2}{\sum [data(t_i)]^2} \right] \times 100$$

(3)
is used, where $data(t_i)$ and $synth(t_i)$ 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-determined parameters and processes for the inversion

On occurrence of a large earthquake in one of the megathrust regions, the fault segment where the hypocenter is located is determined using the preliminary information on source parameters of the earthquake. Then the subfault that harbors the hypocenter within the fault segment is located. Usually, the information on the depth of the hypocenter is less accurate compared to the epicenter, and the informed depth does not coincide with a point on the fault plane of the fault model. Thus the hypocenter depth is moved vertically reaching a point on a nearest subfault to get a new hypocenter depth on the fault plane. We assume that the rupture of the fault initiates from this new hypocenter and propagates along the fault surface with a circular hypothetical rupture front with a reference rupture velocity 3.5 km/s (e.g. an upper limit of the rupture velocity). The upper limit of rupture velocity was determined from the information that most (about 88%) of the estimated rupture velocities of the megathrust earthquakes do not exceed this value, which is based on information from results of forty previous works (Table S1) on modeling of megathrust earthquakes in world-widely distributed subduction zones (i.e., Eastern coast of Japan, western coasts of Mexico and South America, and Sumatra-Andaman region). Most of the information can be also obtained from Finite-Source Rupture Model (SRMOD) Database (Mai and Thingbaijam 2014).

The Green’s function for each subfault is time-shifted by the sum of the reference rupture travel time to each subfault and the delayed time of each time window in the multiple time window scheme. In actual computation, this time-shift process of each Green’s function is done in Fourier domain by shifting phases corresponding to the total delay time.
4. Application to Slip Distribution of 2011 Tohoku-Oki Earthquake

The Great 2011 Mw 9.0 Tohoku-Oki earthquake occurred on March 11, 2011 at 5:46:24 GMT. Its hypocenter was located 38.297° N, 142.372° E, and 30 km depth (USGS National Earthquake Information Center PDE: Preliminary Determination of Epicenter). The strike and dip of the earthquake fault from the USGS CMT solution are 203° and 10°, respectively. 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). The source area corresponds to the fault segment S04 of the Kamchatka/Kurils/Japan subduction zone (Fig. 1) constructed in this research. The strike of the fault segment is 198°, and dips are 6.6°, 12.1°, 16.5°, 19.7°, and 19.3° from the trench to down-dip direction. Using the methods described above, the inversion of full-waveform for the slip process of the Great 2011 Tohoku earthquake was performed.

In order to perform the waveform inversion for slip distribution of the great 2011 Mw 9.0 Tohoku-Oki earthquake, 13 stations covering the azimuth uniformly are selected from 22 available stations that have relatively low noise signals (Fig. 3b). We used Green’s functions computed using the 3D velocity model S362ANI (3Dv) and the fault model based on Slab1.0. The data set from the stations and corresponding Green’s functions are pre-processed as described in the section 3.2 before the inversion. A multiple source time window scheme is applied to the Green’s functions, using 10 source time windows of 20-s isosceles triangular source time function with 10-s overlapping, which corresponds to the subfault source duration time window of 110 s. Least-square inversions of the waveforms for slip distributions are done in the way described in section 3.1. Synthetic seismograms are also computed for the slip
distributions determined by the inversion. Thus, variance reductions are calculated for the waveform similarities between the waveforms of data and synthetics.

The inversion result for the scheme (Fig. 4) shows a predominant slip distribution on the central upper half of the fault with maximum value of 49.51 m near the trench, which is close to the average value 46 m obtained from 26 data sources of previous works (Table 1 of Tajima et al. (2012)). The general location and trend of the major slip distribution is similar to those in the majority of studies done for the earthquake (Hayes, (2011), Simons et al. (2011), Lee et al. (2011), Suzuki et al. (2011), Koketsu et al. (2011), Bletery et al. (2014)), but the shapes of the distributions from most of the studies including ours are different from one another. The approximate width 150 km and length 350 km of the major slip (> 10 m) portion on the fault is close to an average value 158 km and 305 km, respectively, of those from previous results. In addition, smaller minor slip patches with amplitude down to 8 m are found outside of the main rupture area to the north and south. The moment magnitude is 9.05 and most of the slip directs toward ESE in accordance with that from GPS data (Simons et al. 2011) observed in the Northeastern Honshu, Japan. Comparisons of waveforms between the observed and synthetics are shown in Online Resource, Fig. S1. The average variance reduction value for the E, N and Z components of 13 stations is 61.88 %.

The progress of the rupture on the fault plane are represented by snapshots of at every 10 s after the rupture initiation at the hypocenter in Fig. 5. These snapshot distributions correspond to the total slip distribution displayed in Fig. 4. A significant slip in the time interval 0~10 s at the subfault hosting the hypocenter moves to both the downdip and southward directions on the fault in the interval of 10~30 s. In the next interval of 30~50 s, it moves to the up-dip direction reaching the trench. Then the slip spreads along the strike bilaterally in the interval of 50~80 s, covering the widest area
on the fault in the time of 60~80 s. In the interval 80~100 s, the slip is confined to the
shallow area close to the trench. The slip diminishes to insignificant amplitudes in the
time period 100~130 s. The rupture migration pattern is similar to those of Koketsu et
al. (2011), Shao et al. (2011) and Suzuki et al. (2011).

The subfault moment rate functions are displayed at corresponding subfault positions
on the fault (Online Resource, Fig. S2). From the distribution, large moment rates are
found to be concentrated in the central and up-dip portion of the fault. Within the source
time window of each subfault, significant moment rate amplitudes are positioned
properly without truncations of large amplitudes at the beginning and ending times.
This implies that the assumed parameters are properly chosen in the inversion, such as
upper limit of rupture velocity 3.5 km/s as a reference rupture velocity and the subfault
source window length of 110 s corresponding to 10 time windows with 20-s window
length and 10-s overlap.

Subfault moment rate functions are plotted with respect to distances from the
hypocenter to the subfault centers (Fig. 6). The moment rate function of the entire fault
plane is compared with individual subfault moment rate functions in the time-distance
plot. Relatively larger moments are released in the time interval 40~110 s at distances
30~170 km except for a few isolated peaks. Most of the moments are released within
320 km distance and 130 s, and most of subevent ruptures are triggered with apparent
rupture velocities much less than the upper limit of rupture velocity 3.5 km/s with a
minimum apparent rupture velocity of 0.5 km/s. The total moment rate function of the
entire fault plane is compared with individual subfault moment rate functions in the
time-distance plot (Fig. 6, top). It has a triangular shape with the peak at about 70 s
after the hypocenter time.
5. DISCUSSIONS

Comparisons of slip distributions based on different global velocity models and fault dip types:

As mentioned in previous sections, this study uses 3D earth model and 3D numerical model of global subduction zone geometries for finite fault modeling. The seismic waveform inversion for slip distribution of megathrust earthquakes can be done with different earth models and fault geometries. In order to test the effect of earth’s velocity model and fault geometry models on the results of the finite fault, the inversions are done for the four schemes corresponding to combinations of two velocity models and two fault geometry models utilizing the waveform data of the 2011 Mw 9.0 Tohoku-Oki earthquake. The two velocity models are 3D S362ANI (3Dv) and 1D PREM (1Dv). The two fault geometry models are a varying-dip (Vdip) fault model with piecewise-variable dips based on Slab1.0 and a constant-dip fault model with a single dip (Cdip) based on CMT solution with strike of 203° and dip of 10° of the Tohoku earthquake (Online Resource Fig. S3). Thus the four combinations of schemes for velocity models and fault geometry models are denoted by 3Dv-Vdip, 3Dv-Cdip, 1Dv-Vdip, and 1Dv-Cdip.

The slip distributions obtained using the reference rupture velocity 3.5 km/s in the multiple time window scheme for the three pairs of combinations except for the 3Dv-Vdip case are given in Online Resource Figs. S3–S5 (The result for the 3Dv-Vdip is given in Fig. 4). The locations and overall shapes of the significant slip distributions in the three pairs of combination are similar to that of 3Dv-Vdip case, but slip directions and variance reduction values of the waveform fitting are different among pairs of models. The variance reduction values are 55.69 %, 56.36 %, 63.03 %, 61.88 % for 1Dv-Cdip, 1Dv-Vdip, 3Dv-Cdip and 3Dv-Vdip, respectively. In order to see the
contribution of each of the velocity models and each of the fault geometry models to variance reductions, the average variance reduction value is obtained in relation with each of the models. The average variance reduction value 62.45% for 3Dv-related pairs with Vdip (61.88%) and Cdip (63.03%) (Figs. 4 and Online Resource Fig. S3) is larger than 56.02% for 1Dv-related pairs with Vdip (56.36%) and Cdip (55.69%) (Online Resource, Figs. S4 and S5). Thus the 3D velocity model results in much higher variance reduction value than the 1D velocity model. The average variance reduction value 59.12% for Vdip-related pairs with 3Dv (61.88%) and 1Dv (56.36%) (Fig. 4 and Online Resource Fig. S4) is almost the same as 59.36% for Cdip-related pairs with 3Dv (63.03%) and 1Dv (55.69%) (Online Resource Figs. S3 and S5). One of the possible reasons for the similarity for this Tohoku earthquake is that the shallow portions of the fault hosting the main slip distribution have similar dips for the two models of varying dip and CMT-based constant dip. Even though the use of Vdip-related pairs has no advantage in the variance reduction, the ESE directions of the main slip are in accordance with the horizontal coseismic movements of GPS sites in Honshu (Simons et al., 2011; Tajima et al., 2013) in comparison with the results from the Cdip-related pairs showing E or ENE directions of slip. In addition, the piecewise-variable dip model based on Slab1.0 plate interface model gives us much advantage in the availability of digital database of Green’s functions being computed well before the occurrence of the earthquake. Thus it is suggested that the choice of 3D velocity model and the piecewise-varying dip fault model based on the Slab1.0 plate interface model has advantages over the other three combination of models in the aspects of accuracy of the results, and computational convenience and speed. The estimated earthquake magnitudes for all the four cases are close to Mw 9.0.
Comparison of slip distributions based on different fault sizes and reference rupture velocities for 3Dv-Vdip model:

In the finite fault inversion process for a megathrust earthquake, it is not necessary to use the full scale of the pre-determined fault segment. Thus a proper size of the fault is desired to be used, in order to get the slip distribution within a slip area expected for the moment magnitude and thus to achieve computational efficiency. Goda et al. (2018) presented new scaling relationships of earthquake source parameters using finite fault rupture models from the database of SRCMOD. The scaling relationships are based on a vast data set including most recent megathrust earthquakes such as the 2011 Mw 9.0 Tohoku earthquake, which are compared to those of Mai and Beroza (2002) for crustal earthquakes with magnitude up to Mw 8.0. According to the relationship of Goda et al. (2018) for the fault area and moment magnitude of tsunamigenic earthquakes, the expected rupture area of the Mw 9.0 (the 2011 Tohoku earthquake) amounts to 105,877 km$^2$, which corresponds to about 42 subfaults with area of 50 x 50 km$^2$ each. Thus a finite fault inversion was done using only 40 subfaults of the total 75 in the fault segment for the 2011 Mw 9.0 Tohoku earthquake. The 3D velocity model and the varying-dip fault model (3Dv-Vdip model) were used with maximum rupture velocity of 3.5 km/s in multiple time window scheme. The resulting slip distribution (Online Resource Fig. S5a) is similar to the distribution obtained using the all subfaults in the full-scale fault segment (Fig. 4), except for a little larger peak slip by 5 m in the major slip patch and no minor slip patch with significant amplitude around the main slip patch.

We performed experimental teleseismic waveform inversions for the 2011 Tohoku earthquake using a sequence of the upper limit of rupture velocities 1.1~4.0 km/s with the scheme of all the 75 of subfaults in the fault segment with the 3Dv-Vdip model. The resulting slip distributions show that the overall shapes of the main slip
distributions are the same. However, as the rupture velocities decrease, minor slip patches at the northeast of the main slip portions shift towards the center of the main slip and finally merge and the maximum amplitudes of the main slips become slightly larger. The phenomena are prominent for the cases of rupture velocity lower than 2.0 km/s. The slip distribution for the rupture velocity 1.7 km/s (Online Resource Fig. S5b), as an example, shows the main slip patch with a smaller covered area and a larger peak slip (about 71 m) compared to those for the reference rupture velocity of 3.5 km/s. There are no minor slip patches around the main patch to the north and south, which were found for the case of 3.5 km/s.

**Computations of the tsunami using different slip distributions based on the 3Dv-V dip model.**

We also tried to simulate tsunamis based on the slip distributions from different fault sizes and reference rupture velocities for the 3Dv-V dip model using the software Clawpack 5.2.0 (Clawpack Development Team 2014) to check if the slip distributions are applicable to tsunami forecast. The software calculates initial sea surface deformation due to the slip distribution on inclined shear 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 the effects of seafloor bathymetry change. We used NOAA ETOP01 1-minute Global Relief grid database with 4-minute grid space model for the bathymetry effect. Synthetic tsunami waveforms are computed for four DART buoys located to the east off-shore of Honshu, using slip distributions (Fig. 4, Online Resource Fig.s S5a, and S5b) from the finite fault inversions for the three combination schemes depending on two cases of the fault size (75 and 40 subfaults, represented hereafter by Nsub75 and Nsub40, respectively)
and two cases of the reference rupture velocity (3.5 km/s and 1.7 km/s, represented hereafter by Vr3.5 and Vr1.7, respectively) excluding the combination of 40 subfaults and 1.7 km/s. The results are compared with observed waveforms (Fig. 7). The four buoys are DART #21418, #21401, #21419, #21413 in the order of increasing distance and the clockwise directions from the epicenter of the earthquake.

The overall tsunami waveform at each buoy station consists of the leading pulse of a large positive amplitude followed by a smaller negative pulse. General shapes and arrival times of synthetic waveforms appear fit to those of observed ones (Fig. 7). However, a precursory signal with a significant amplitude arrives before the main positive pulse in the synthetics for the case of the full-scale fault model with reference rupture velocity 3.5 km/s (Nsub75 & Vr3.5) at stations DART#21401 and DART#21419, which is not found in the observed waveform. Consequently, the main pulses are affected by the precursor signal and have smaller amplitude than the observation. The precursory signals are caused by the small anomalous patch in the computed slip distribution in the northeastern part of the full-scale fault model (Fig. 4). Such precursory signals are not seen in the synthetic traces of the other two cases (Online Resource Figs. S5a & S5b for slip distributions, and Fig. 7 for tsunamis): the one for reduced fault size with the reference rupture velocity 3.5 km/s (Nsub40 & Vr3.5) and the other for the full-scale fault model with reduced reference rupture velocity 1.7 km/s (Nsub75 & Vr1.7). In an effort to match the tsunami data, various test inversions using different sizes of fault and different maximum rupture expansion speeds were done. We find that either reducing the fault size according to the moment magnitude Mw 9.0 or lowering the maximum rupture expansion speed eliminates the anomalous slip distribution causing the precursory tsunami signal (Fig. 7), without significantly compromising the waveform fit of seismic data (Online Resource Fig. S5). We interpret
the phenomena in two ways: The first one is that a fault setting of unnecessarily large size compared to the moment magnitude of the earthquake might cause numerical errors possibly due to data noise, and thus causes some minor fictitious slip patches and corresponding signal in tsunami simulations. The second interpretation is that some slip patches triggered with very large rupture velocities in the inversion are not in accordance with proper generation of tsunami using the theoretical methodology used in the study.

The peak amplitude differences of the leading dominant phase between the observed and synthetic traces (synthetic minus data) at each buoy station ranges from -0.40 to +0.42 m (Online Resource, Fig. S6). The difference for the case of the full-scale fault with the reference rupture velocity 3.5 km/s (Vr3.5 & Nsub75) ranges from -0.40 m to -0.12 m, that for the reduced fault size with the reference rupture velocity 3.5 km/s (Vr3.5 & Nsub40) ranges from -0.02 m to 0.20 m, and that for the full-scale fault with the lower reference rupture velocity 1.7 km/s ranges from -0.10 to 0.42 (Vr1.7 & Nsub75). There is no special preference of ours, even though the case of reduced fault size has smallest misfit of amplitude among the three cases. In order to refine the fault slip distribution model, the inversion scheme may need to be constrained by geodetic and/or tsunami data.

6. CONCLUSIONS

We present a technique of the teleseismic waveform inversion for determination of a megathrust rupture process using finite fault models with varying dips based on a plate interface geometry model Slab1.0 and using synthetic Green functions computed
with SEM in laterally heterogeneous 3D mantle model S362ANI and 3D crust velocity model CRUST2.0. The primary purpose is to obtain large spatial-scale slip distributions as soon as possible right after occurrences of megathrust earthquakes in subduction zones. The method employs the multiple time window scheme for the subfault source time function in order to enhance the accuracy of the inversion results and to avoid the effort for finding proper rupture velocity. The method does not need priori information on the focal mechanism determined by CMT or W-phase solutions. Thus the geometry of the fault plane with subfaults and corresponding Green’s functions for pre-determined global seismic stations can be computed and stored before the earthquake, and at occurrence of a megathrust earthquake, the rupture process can be computed in a relatively short time using the stored Green’s functions.

The finite fault models with varying dips are constructed for 11 global megathrust regions in the circum-Pacific regions, and thus are more realistic and accurate than the single-dip fault model from the CMT or W-phase solution. The validity accuracy of the inversion is proved enhanced by using the teleseismic Green’s functions in laterally heterogeneous global 3D velocity models, which was convinced by comparison tests for the performances of the 1D and 3D models in the forward synthetics using data from a foreshock of the 2011 Mw 9.0 Tohoku-oki earthquake and in the inverse modeling for the mainshock slip process. The most prominent role of the 3D velocity model is coming from the behavior of teleseismic surface waves which is important in estimation of large scale slip distributions.

Green’s functions for all the subfault-station pairs for seismic stations of worldwide networks are computed and stored in a Green’s function database before the earthquakes. With the 2606 modeled subfaults in the circum-Pacific region, 177 worldwide stations, 2 rake directions and 3 components, the total number of Green
functions calculated are 2,767,572. Right after a megathrust earthquake, the slip
distribution could be obtained in a few hours depending on data quality and/or
azimuthal coverage of stations, considering times for data acquisition and
preprocessing of data, since the CPU time for the inversion itself is less than 10 minutes
and the search for optimum rupture velocity is not required in the multiple time window
scheme.

Most accurate results for the rupture processes using the scheme could be
obtained by using constraints of geodetic and/or tsunami data. Even if the method is
formulated for the teleseismic waveform inversion, it could be extended to a case of
multi-data set including geodetic near-source displacements recorded by GPS and
tsunami waveform data from DART buoy observations, with proper relative weighting
between data sets, such as those in previous works (Rhie et al., 2004; Delouis et al.,
2010; Koketsu et al., 2011). Green’s functions of geodetic displacements for sets of
subfault-station pairs could be computed and stored as database to be used at the time
of an earthquake. With these facilities of additional constraints to complement the
seismic data set, some type of automatization process in all computational processes
including data preparations and the inversion could lead to a possibility for the
mitigation of seismic and/or tsunami hazards in the future. Since the purpose of the
research is not directly related to the early warning of seismic or tsunami hazards, we
do not attempt to develop an automatized device for all the inversion process at this
time.
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REFERENCES


Clawpack Development Team (2014) Clawpack software vol 5.2.0, 5.2.0 edn.,


Hayes GP (2011) Rapid source characterization of the 2011 Mw 9.0 off the Pacific Coast of Tohoku earthquake Earth Planets Space 63:529-534


Okada Y (1992) Internal deformation due to shear and tensile faults in a half-space Bulletin of Seismological Society of America 82:1018-1040


Shao G, Li X, Ji C, Maeda T (2011) Focal mechanism and slip history of the 2011 Mw 9.1 off the Pacific coast of Tohoku Earthquake, constrained with teleseismic
body and surface waves Earth, Planets and Space 63:559-564
doi:10.5047/eps.2011.06.028

Simons M et al. (2011) The 2011 magnitude 9.0 Tohoku-Oki earthquake: mosaicking
the megathrust from seconds to centuries Science 332:1421-1425
doi:10.1126/science.1206731

Tohoku-Oki mega-thrust earthquake (M9.0) inverted from strong-motion data
Geophysical Research Letters 38:n/a-n/a doi:10.1029/2011gl049136

(Mw 9.0): Large-scale rupture across heterogeneous plate coupling

doi:10.1029/2011JC007635

Seismology Communications in Computational Physics 3:1-32

Inversion of Real-Time Tsunami Waveforms and Seismic or GPS Data:
Application to the Tohoku 2011 Tsunami Pure and Applied Geophysics
171:3281-3305 doi:10.1007/s00024-014-0777-z

Harvard University Press, Cambridge, MA


Yoshida Y, Ueno H, Muto D, Aoki S (2011) Source process of the 2011 off the
Pacific coast of Tohoku Earthquake with the combination of teleseismic and
strong motion data Earth, Planets and Space 63:565-569
doi:10.5047/eps.2011.05.011

Yoshimoto M, Yamanaka Y (2014) Teleseismic inversion of the 2004 Sumatra-
Andaman earthquake rupture process using complete Green’s functions Earth,
Planets and Space 66

Earthquake from Joint Inversions of High-Rate Geodetic and Seismic Data
Bulletin of the Seismological Society of America 103:1242-1255
doi:10.1785/0120120119

Figure Caption

Fig. 1 Distribution of varying-dip finite fault models constructed based on subduction-zone plate interface geometry model USGS Slab 1.0. There are 11 subduction zones modeled: Alaska-Aleutian (ALU), Central America (MEX), Cascadia (CAS), Izu-Bonin (IZU), Kermadec-Tonga (KER), Kamchatka/Kurils/Japan (KUR), Philippines
(PHI), Ryukyu (RYU), Santa Cruz Islands/Vanuatu/Loyalty Islands (VAN), Solomon Islands (SOL), South America (SAM), and they are assigned with white characters. The location of the modeled finite fault for each fault segment in this study is marked by a rectangle. The segments in each subduction zones are numbered in a sequential order with black characters (i.e. S01, S02, … ). Each fault segment consists of subfaults defined by depths, strikes and dips at locations in longitudes and latitudes. The depths of the Slab1.0 are represented by colored scale in km. The fault segment in which the 2011 Tohoku-oki earthquake occurred is marked by an asterisk next to the segment number. The colored scale bar indicates the depths of subducting plates

**Fig. 2** Comparison of observed broadband vertical component waveforms and synthetics by the spectral element method (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 (hypocenter of 38.56° latitude, 142.78° longitude, depth 14.1 km, with fault plane of strike 189°, dip 12°, rake 78°). Larger deviations are found for the synthetics in 1D model compared to 3D model

**Fig. 3** (a) 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, green are GEOSCOPE, black are
GEOFON, and blue are MEDNET networks. Total number of stations is 177 and corresponding total number of Green’s functions is 2,767,572.

(b) Global locations of stations used in the exemplary finite fault inversion for 2011 Mw 9.0 Tohoku earthquake. The stations are located at epicentral distances 30° ~ 90° and have relatively uniform azimuthal coverage.

Fig. 4 Slip distribution from the finite fault inversion of the teleseismic full waveforms for the 2011 Mw 9.0 Tohoku earthquake using the 3D S362ANI velocity model and the fault model based on Slab1.0 with a constant strike (Segment S04 in KUR region). Maximum allowed rupture velocity of 3.5 km/s and 10-time windows of 20-s duration with 10-s overlap for each subfault source time function were used in multiple time window scheme. The resulting Mw was 9.1, and variance reduction of waveform fit was 61.88%. Slip distribution with amplitudes and directions is represented by colors and arrows, respectively. The Inset at the bottom shows A-A’ vertical cross section of the fault with varying-dips in degree. W01~W05 indicate subfaults with location numbers counting from the trench. The vertical and horizontal distances are in the same scale.

Fig. 5 10-s interval snapshots of finite fault slip distributions from the teleseismic full waveform inversion using the multiple time window scheme for the 2011 Mw 9.0 Tohoku Earthquake. These snapshot slip distributions correspond to the total slip distributions displayed in Figure 4. The subfault-hosting the hypocenter is triggered within the first time step 0~10-s interval. In the interval of 10~30 s, significant slip moves to the west and south on the fault. In the next interval of 30~60 s, it moves to the up-dip direction reaching the trench. Then the slip spreads along the strike.
bilaterally in the interval 50~80 s covering the widest area on the fault in the time of
60~80 s. In the interval 80~100 s, the slip is confined to the shallow area close to the
trench. The slip diminishes to insignificant amplitudes after the time period
100~110 s. The small yellow star represents the hypocenter of the earthquake

**Fig. 6** Subfault moment rate functions with respect to distances from the hypocenter
to the subfault center in the teleseismic full waveform inversion using the multiple
time window scheme for the 2011 Mw 9.0 Tohoku Earthquake. The moment rate
function of the entire fault plane (top) is compared with individual subfault moment
rate functions in the time-distance plot (bottom). Relatively larger moments are
released in the time interval 50~110 s at distances 30~180 km except for a few
isolated peaks. Most of the moments are released within 320 km distance and 130 s.
Most of subevents triggered with apparent rupture velocities much less than the
maximum velocity 3.5 km/s. These moment rate functions correspond to the slip
distribution displayed in Fig.s 4 and 5

**Fig. 7** Results of tsunami simulations using slip distributions from multiple time
window finite fault inversions based on different fault sizes and reference rupture
velocities for the 2011 Tohoku-Oki earthquake. The fault model composed of entire
fault segment is marked by the blue rectangle, and the reduced fault model according
to Mw 9.0 is marked by the red rectangle on the map. The black traces are the
observed waveform. Gray (Vr3.5, Nsub75) and blue traces (Vr1.7, Nsub75) are the
simulated results using the entire fault model of 75 subfaults, with maximum allowed
(reference) rupture velocity of 3.5 km/s and 1.7 km/s, respectively. Red traces (Vr3.5,
Nsub40) are the simulated results using the reduced fault model of 40 subfaults, with
reference velocity of 3.5 km/s. All simulated results are obtained in the multiple time window scheme with 10-time windows of 20-s duration and 10-s overlap for each subfault source time function.
Fig. 2
Fig. 5
Fig. 7
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