Spatio-temporal afterslip distribution following the 2011 Tohoku-Oki earthquake using 3D viscoelastic Green’s functions

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Abstract. On March 11, 2011, the Tohoku-Oki earthquake (Mw 9.0) occurred on the plate interface of the subducting Pacific plate. During the co- and post-seismic periods, almost all GEONET and seafloor observations detected eastward crustal deformation. However, seafloor observations around main raptured zone moved in a westward direction during the post-seismic period. In this study, we estimate the spatio-temporal slip distribution during the co- and post-seismic periods from observed crustal deformations, such as GEONET and seafloor observations. For inversion, we use a viscoelastic Green’s function derived from a three-dimensional finite element method considering the underground structure. The estimated maximum co-seismic slip is approximately 60m from the Japan Trench. Off Iwate prefecture, the moment magnitude and maximum afterslip 2.5 years after the Tohoku-Oki earthquake are approximately 8.13 and 2.0m, respectively. The afterslip distributions differ from the co-seismic slip distribution, and the relationship between the co-seismic and afterslip regions is complementary.

Introduction

To study the physics of earthquakes, observations of earthquake ruptures and spatio-temporal distribution of afterslips are required. The co- and post-seismic observations of the deformation associated with a large earthquake, provide the spatio-temporal distribution of fault mechanical parameters around source region [e.g., 1, 2, 3]. After a large subduction earthquake, observed postseismic deformation includes viscoelastic relaxation of stresses induced by the earthquake and afterslip [e.g., 4, 5]. It is commonly assumed that short-term (a few years) deformation near the rupture zone is caused mainly by afterslip, and that viscoelasticity is important only for longer-term deformation.

In 1996, the Geospatial Information Authority of Japan established national the GNSS observation network (GEONET), which consists of approximately 1200 GNSS sites. Following the March 11, 2011 Tohoku-Oki earthquake (Mw 9.0), GEONET observed the time evolution of post-seismic crustal deformation, including the effects of several phenomena, such as afterslip and viscoelastic responses (i.e., stress relaxation at the lower crust or upper mantle). The direction of horizontal crustal deformation on land due to afterslip is oriented in approximately the same direction as the co-seismic deformation because both dislocations of co-seismic and afterslip on the plate interface are oriented in the reverse fault slip direction. The viscoelastic crustal deformation on land due to co-seismic slip is also in the same direction [e.g., 4, 5]. Thus, it is difficult to distinguish afterslip from viscoelastic response without seafloor geodetic observation and/or computer simulations.

Watanabe et al. [6] observed significant post-seismic movements following the 2011 Tohoku-Oki earthquake, based on seafloor geodetic observation along the Japan Trench. Trench-normal movements around main raptured zone were smaller than other offshore regions. Watanabe et al. [6] pointed out these post-seismic movements at offshore are consist with effects predicted from viscoelastic relaxation in the upper mantle.

In this study, we have attempted to estimate viscoelastic response resulting from the 2011 Tohoku-Oki earthquake using a three-dimensional (3D) finite element method (FEM). If viscoelastic response is not considered, it is not...
possible to evaluate afterslip properly. We use a viscoelastic Green’s function (vGF) to consider 3D underground structures. We extract the co- and post-seismic displacements resulting from the 2011 Tohoku-Oki earthquake from observed crustal deformation on land and the seafloor. We also estimate the spatio-temporal slip distributions during co-seismic and post-seismic periods and discuss the features of the afterslip and viscoelastic effects.

Observation Data

To estimate the co-seismic and afterslip distributions using spatiotemporal slip of co- and post-seismic vGF, which is derived from 3D FEM calculations, we use the time evolution of crustal deformation from GEONET and seafloor observations. Available geodetic data include daily coordinates from GEONET GPS stations, seafloor displacements from GPS/Acoustic (GPS/A) stations, and seafloor vertical displacement from ocean-bottom pressure (OBP) gauges.

GEONET data

Observed time evolution of crustal deformation includes linear trends, annual and semi-annual variations, and co- and post-seismic deformations. To extract the time series of post-seismic deformation following the 2011 Tohoku-Oki earthquake, we model the observed time series of crustal deformation, $x(t)$, as follows:

$$x(t) = a_1 + a_2 t + \sum_{i=1}^{2} \left( a_{1+i} \sin \left( \frac{\pi t}{365.25} \right) + a_{2+i} \cos \left( \frac{\pi t}{365.25} \right) \right) + \sum_{j=1}^{eq} \left( a_{4+3j} H_j(t) + a_{5+3j} \log \left( 1 + \frac{t - T_j}{a_{6+3j}} \right) \right) + e(t)$$

(1)

where, $a$ are model parameters, $t$ is time, $H_j(t)$ is a Heaviside function relating to co-seismic step, $e(t)$ is error, $j$ is the number of large earthquakes, and $T_j$ is the time of each large earthquake. The large earthquake are selected GEONET which are observed coseismic step due to several large earthquakes ($M_{JMA} > 7.0$), which is based on the Japan Meteorological Agency earthquake catalogue. The modeled earthquakes are only observed co-seismic step at a GNSS site. The number of $eq$ in Eq.(1) is different between each GNSS site. In order to remove crustal deformation due to the afterslip of other local earthquake, we predict post-seismic deformation using Eq.(1). The model can predict post-seismic deformation with a logarithmic evolution, which projects the time evolution of afterslip, assuming a velocity-strengthening brittle creep rheology [7]. Eq.(1) dose not consider to time evolution of surface deformation due to viscoelastic relaxation of stress. The residual of Eq.(1) is including observation error of GNSS analysis and the time evolution of surface deformation due to viscoelastic relaxation. The post-seismic deformation following the 2011 Tohoku-Oki earthquake consists of afterslip component due to the 2011 Tohoku-Oki earthquake and residual in Eq.(1).

To estimate the spatio-temporal slip distribution including the co-seismic period, we use the co- and post-seismic displacements at 6-month intervals for 2.5 years after the 2011 Tohoku-Oki earthquake (Figures 1(d) and (e)). For geodetic inversion, we remove annual and semi-annual variations, co-seismic step, and afterslip due to aftershocks using the modeled time evolution of crustal deformation based on Eq.(1). Hence, our model focus on aseismic afterslip process along plate interface.

Seafloor GPS/A and OBPs Data

We use observed seafloor crustal deformation from GPS/A stations and OBP gauges off Tohoku district. To estimate the co-seismic slip distribution on the plate interface, we use seafloor crustal deformation estimates performed by Tohoku University, the Earthquake Research Institute of the University of Tokyo, and the Japan Coast Guard (JCG) using seven GPS/A and 12 OBP observations (Figure 1(d)) [8, 9, 10, 6]. To estimate the co-seismic slip distribution on the plate interface, we use displacements at seven GPS/A and 12 OBP stations. For the post-seismic period, we use data from six GPS/A sites (Figure 2).
Method

The 3D Model for FEM

Previous studies have demonstrated that surface displacements are significantly influenced by three-dimensional variations of material properties [11, 12, 13]. Consequently, we used PyLith v2.0.0 to determine GFs using FEM. PyLith software is designed to simulate crustal deformation over a wide range of spatio-temporal scales [14]. Figure 1(a) shows the model region (length 2600km, width 1500km, height 400km). There are 3,205,950 nodes and 3,121,200 cells in the FEM mesh. The average length of a cell is approximately 7km; cells close to the plate interface are approximately 2 km in length. We consider the topography of the FEM mesh close to land and trench regions. This subsurface structural model is based on the iso-depth contours of the Conrad and Moho planes [15, 16] and of the upper plane of the Pacific plate [17, 18]. The boundary conditions on the sidewalls and bottom of the model area are applied to the roller conditions, which are fixed displacements in the normal direction to each boundary. Figure 1(b) shows a map view of sub-faults; the number and size of sub-faults are 946 and 110-270 km², respectively. The slip direction of each sub-fault assumes plate motion [19], and a slippery node technique is used to express the slip dislocation [20]. The 3D FEM mesh is divided into six regions: Upper Crust, Lower Crust, Upper Mantle, Oceanic Crust (Layer 2 and Layer 3), and Oceanic Mantle (Figure 1(c)). we use that the viscosity of upper mantle is 4 × 10¹⁸ Pa·s, which is based on the viscoelastic response following the 2008 Iwate-Miyagi Nairiku earthquake [21] and the 1993 South-West off Hokkaido earthquake [22]. Although, the viscosity is lower than other layer subsurface structural model [4, 23], actual relaxation time of our model, which consider elastic subducting plate, is longer than previous layer model. Table 1 shows the material properties (Vₚ, Vₛ, density, and viscosity) at each region.

Inversion method

We estimate the spatio-temporal slip distribution mₗ(τ) at sub-fault (j) on the plate interface, using the vGF, Gᵥi j(t; τ), which is derived from a 3D FEM calculation. The surface displacement dᵢ(t) at observation site (i) on the surface at time (t), which is the elapsed time from the 2011 Tohoku-Oki earthquake, from integration over time can be expressed as:

\[
dᵢ(t) = \sum_j^J \int_0^\infty Gᵥi j(t − τ; 0)mₗ(τ)dτ + eᵢ(t)
\]

(2)

Here, τ and eᵢ(t) are modeling time on the plate interface and random measurement error, respectively. Equation (2) represents the surface displacement expressed as the convolution of the vGF and the time evolution of slip on the plate interface. We consider viscoelastic response due to coseismic slip and afterslip along the plate interface. Thus, the co- and post-seismic displacements are modeled by the sum of the following four components: elastic and viscoelastic responses to coseismic slip and elastic and viscoelastic responses to afterslip on the plate interface.

We employ a priori information of slip distribution in our inversion scheme. Specifically, we add a constraint, i.e., the spatial Laplacian of slip is nearly zero at each time step, which is expressed as follows:

\[
0 = ∆mₗ(τ) + e
\]

(3)

Here, ∆ is the Laplacian operator. To obtain the spatio-temporal slip distribution, we combine Eq. (2) and Eq. (3) using two hyper parameters (αc for co-seismic and αp for post-seismic periods) that control the strength of a priori information as follows:

\[
\begin{pmatrix}
    d \\
    0
\end{pmatrix} = \begin{pmatrix}
    G \\
    αS
\end{pmatrix}m
\]

(4)

Here, G and S are a vGF matrix and smoothing matrix, respectively. To solve Eq. (4), we employ a constrained least square method in which slip velocities are constrained to not exceed plate subduction velocity (>~10cm/year), because modeled region consists of afterslip region and still coupling region on the plate boundary. In our inversion method, we consider viscoelastic response due to co-seismic and viscoelastic response due to afterslip. We select hyperparameters α based on Akaike’s Bayesian Information Criterion [24].

Relative weights of different types/components of data are an important issue in inverse solution. We use weights of data as variance of data, which estimate variance of GEONET data from eᵢ(t) in Eq.(1). Variances of GPS/A and
OBP data are reported by [6, 8, 9, 10]. However, we set the weight of the GPS/A and OBP data to be 100 times stronger than GEONET data because sea floor observation sites are limited and isolate from GEONET. GEONET stations are distributed only in land, and mean distance between stations is about 20km. Therefore, the correlation among nearby stations of GEONET site is large. The covariance among GEONET stations make relatively downweight GEONET data for other data set [25]. It should be offset by more weight on GPS/A and OBP data. Note that [26] use $10^4$ times heavier weights for GPS/A and OBP data compared to GEONET data.

**Result and Discussion**

**Co-seismic Slip Distribution**

Figure 3(a) shows estimated co-seismic slip distributions from GEONET, seafloor GPS/A and OBP data. The main rupture (>30m) is located around the hypocenter and shallower (<30km) region, which is approximately 200km long in the direction parallel to the trench and 100km wide in the direction normal to the trench. The maximum slip is approximately 60m and is located close to the trench. Our results are consistent with previous studies that have used seismic waveform and/or GPS data to determine that very large co-seismic slips (>45m) occur close to the trench [e.g., 26, 27, 28]. The relatively small rupture area (approximate 10m) is located in a deeper portion of the epicenter (approximately 30-50km deep) near the coastline of Miyagi prefecture in an area approximately 150km long and 50km wide. We suggest that our target rupture area overlaps the rupture area of the 1978 Miyagi-Oki (M 7.4) earthquake. Figure 1(d) shows observed and simulated co-seismic displacements. The residual displacement pattern of co-seismic period on land is in eastward and subsidence directions. The maximum residual displacements are approximately 80cm (horizontal) and 30cm (vertical) close to the Pacific Ocean coastline. In seafloor observations, the residual pattern is in almost random directions and the maximum amount is 90cm.

**Spatio-temporal Afterslip Distribution**

Figures 3(b-f) show snapshots of spatio-temporal afterslip distribution for each half year. The main afterslip is off Iwate Prefecture; the maximum afterslip (15-45km depth) reached approximately 2.0m up to September, 2013. The down-dip limit of the afterslip region is approximate 60km in depth and almost corresponds to a coastline. In the inter-seismic period, the down-dip limit of interplate coupling is approximately 60km in depth and almost corresponds to the afterslip region [e.g., 29, 30]. The estimated afterslip following the 2011 Tohoku-Oki earthquake occurred in an area further north, further south, and deeper than the co-seismic slip area. The afterslip distribution differs from co-seismic slip distribution; however, the relationship between co-seismic and after slips regions is complementary. Figure 4(a) shows aftershocks and afterslips in early periods. The dominant afterslip area is located off Iwate Prefecture; aftershocks occurred around the afterslip area and some overlapped with the afterslip area [31]. The aftershocks around the co-seismic slip region primarily occurred at a depth of approximately 60km. In particular, aftershocks occurred in the down-dip extension region of the afterslip area. There is a possibility that aftershocks induced afterslips. In previous studies, complementary relationships, such as the 2003 Tokachi-Oki earthquake (M 8.0) [32] and the 1994 Sanriku-Haruka-Oki earthquake (M7.6) [33], suggest the generality of separation between the afterslip and co-seismic slip areas in cases of large subduction earthquakes.

The estimated seismic moment of afterslip increases over time; for example, the estimated seismic moment of afterslip a year after the 2011 Tohoku-Oki earthquake is 7.96. Logarithmic evolution of cumulative estimated seismic moment indicates an increase of up to 8.13 at the end of 2013. The released seismic moment percentages of post-seismic and co-seismic events at 1.0 and 2.5 years after the 2011 Tohoku-Oki earthquake are 4.8% and 8.6%, respectively. Compared to the 1994 Sanriku-Haruka-Oki earthquake (M 7.6), the released post-seismic moment magnitude following the 1994 Sanriku-Haruka-Oki earthquake was 7.7 one year later, which is larger than the released co-seismic moment [34]. In the 2003 Tokachi-Oki earthquake (M 8.0), the seismic moment magnitude of afterslip following the 2003 Tokachi-Oki earthquake was approximately 7.8, which is almost equivalent to the main event [32]. Based on previous studies [e.g., 32, 34], the ratio of released post-seismic moment magnitude to co-seismic is much smaller for the 2011 Tohoku-Oki earthquake than that of the 1994 Sanriku-Haruka-Oki and 2003 Tokachi-Oki earthquakes because the ruptured area of the 2011 Tohoku-Oki earthquake is wider than other events and the area where afterslips could possibly occur is not large. In this region, we suggest that the limitation of down-dip of the afterslip region corresponds to the down-dip limit of interplate coupling region [29, 30].
Figure 1(e) shows observed and simulated post-seismic displacements on land 2.5 years after the event. The maximum residual of the horizontal component 2.5 year after the event is approximately 10cm. The time evolution of residual patterns on land is similar during post-seismic periods. Figure 2 represents time evolution of observed and simulated displacement on the seafloor. Our model fits very well for the observed displacement, which including displacement in a westerly direction, such as the KAMS and MYGI sites.

**Comparison of elastic and viscoelastic responses**

Our model explains the spatio-temporal patterns of postseismic deformation (see figure 2). Visco-elastic response can explain roughly postseismic deformation [5]. However, postseismic deformation cannot explain only visco-elastic response due to the 2011 Tohoku-Oki earthquake, but also afterslip on the plate interface. Our results indicate that previous models assuming an elastic Earth will have substantially overestimated afterslip down-dip of the rupture zone, and underestimated afterslip up-dip of the rupture zone [2].

Figure 4(b) represents the estimated afterslip distribution 2.5 years after the 2011 Tohoku-Oki earthquake, using the elastic Green’s function (eGF). When results from eGF and vGF estimates are compared, large differences in afterslip distribution are evident. For eGF, the maximum afterslip off Fukushima prefecture 2.5 after the event is approximately 4.0m, which approximately two times larger than estimates using vGF. The afterslip distribution reported by Ozawa et al. [2] is similar to our spatio-temporal afterslip distribution using eGF. The primary difference between eGF and vGF techniques for afterslip is peak location (Figures 3(f) and 4(b)). Off Fukushima prefecture, the afterslip peak using eGF strongly depends on viscoelastic response due to the co-seismic slip, which is located close to the Japan trench and shallower than the main afterslip region using eGF. Using eGF, the viscoelastic response pattern due to the 2011 Tohoku-Oki earthquake is similar to the post-seismic displacement due to the afterslip off Fukushima. Hence, on the basis of vGF, the afterslip off the Fukushima is smaller. Thus, it is evident that it is important to consider viscoelastic response.

**Conclusion**

In this study, we estimate spatio-temporal distribution of co- and post-seismic slips in the 2011 Tohoku-Oki earthquake using geodetic data from GEONET and seafloor observations. In inversion, vGF derived from 3D-FEM is used to evaluate the effects of the 3D subsurface structure characteristics, such as material property and plate subduction geometry. Inverted co- and post-seismic slip distributions are considered an effect of viscoelastic response using an observation equation with a built-in viscoelastic response. The maximum amount of co-seismic slip is approximately 60m close to the Japan Trench. The dominant co-seismic slip is located at depth less than 30km. Afterslips primarily occur off Iwate prefecture. The maximum amount of post-seismic slip is approximately 2.0m. When eGF is used, the dominant afterslip is approximately 4.0m off Fukushima, and there is a possibility of overestimating. The relationship of co- and post-seismic slip regions is complementary. When afterslips and the distribution of aftershocks are compared, there is a possibility that afterslips induce aftershocks. The moment magnitude of the afterslip was 8.13 after 2.5 years from the 2011 Tohoku-Oki earthquake.

**TABLE 1.** Material properties of each region in Figure 1(c). P- and S-wave velocities : [35, 36, 37], Density : [38, 39, 40], Viscosity : [21, 22]

<table>
<thead>
<tr>
<th>Regions</th>
<th>(V_p) (m/s)</th>
<th>(V_s) (m/s)</th>
<th>Density (kg/m(^3))</th>
<th>Viscosity (Pa·s)</th>
</tr>
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<tr>
<td>Upper Crust</td>
<td>6040</td>
<td>3550</td>
<td>2670</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Lower Crust</td>
<td>6610</td>
<td>3760</td>
<td>3000</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Upper Mantle</td>
<td>7730</td>
<td>4340</td>
<td>3360</td>
<td>(4.0 \times 10^{18})</td>
</tr>
<tr>
<td>Oceanic Crust (Layer2)</td>
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<td>3117</td>
<td>2840</td>
<td>(\infty)</td>
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<tr>
<td>Oceanic Crust (Layer3)</td>
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<tr>
<td>Oceanic Mantle</td>
<td>8400</td>
<td>4800</td>
<td>3360</td>
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</table>
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FIGURE 1. (a): The red rectangle is the 3D FEM mesh model region. The A-B line A-B denotes the cross-section shown in Figure 1(c). (b): Sub-faults on the plate interface. (c): Cross-section along A-B in Figure 1(a). (d) Co-seismic offsets derived from GEONET and seafloor observations (black and green arrows denote horizontal components, blue and red bars denote vertical components). The gray and light green arrows represent the simulated co-seismic horizontal offsets. The light red and light blue bars represent the simulated co-seismic vertical offsets. The yellow star indicates the epicenter of the 2011 Tohoku-Oki earthquake. (e) Post-seismic offsets derived from GEONET (black arrows denote horizontal components). The post-seismic period is from March 12, 2011 to September 12, 2013. The red squares denote seafloor GPS/A sites.
FIGURE 2. Time evolution of post-seismic deformation at three components of sea floor observations. Blue and red dashed lines show observed and simulated displacements. Observation sites on the sea floor are shown in Figure 1(e).
FIGURE 3. Inverted spatio-temporal slip distribution considering 3D viscoelastic structure. (a): Co-seismic slip distribution, (b-f): Snapshots of cumulative afterslip distribution at 0.5 year intervals from the 2011 Tohoku-Oki earthquake. (b) 0.5, (c) 1.0, (d) 1.5, (e) 2.0, (f) 2.5 years.
FIGURE 4. (a) Inverted afterslip distribution for a half year with aftershocks. The distribution is mapped 2.5 months after the 2011 Tohoku-Oki earthquake [31]. (b) Inverted afterslip distribution 2.5 years after the Tohoku-Oki earthquake using eGF.