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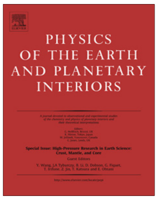

An adjoint-based FEM optimization of coseismic displacements following the 2011 Tohoku earthquake: new insights for the limits of the upper plate rebound

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ABSTRACT

The 11 March 2011 Tohoku earthquake was the strongest event recorded in recent historic seismicity in Japan. Several researchers reported the deformation and possible mechanism as triggered by a mega thrust fault located offshore at the interface between the Pacific and the Okhotsk Plate. The studies to estimate the deformation in detail and the dynamics involved are still in progress. In this paper, coseismic GPS displacements associated with Tohoku earthquake are used to infer the amount of slip on the fault plane. Starting from the fault displacements configuration proposed by Caltech-JPL ARIA group and Geoazur CNRS, an optimization of these displacements is performed by developing a 3D finite element method (FEM) model, including the data of GPS-acoustic stations located offshore. The optimization is performed for different scenarios which include the presence of topography and bathymetry (DEM) as well as medium heterogeneities. By mean of the optimized displacement distribution for the most complete case (heterogeneous with DEM), a broad slip distribution, not narrowly centered east of hypocenter, is inferred. The resulting displacement map suggests that the beginning of the area of subsidence is not at east of MYGW GPS-acoustic station, as some researchers have suggested, and that the area of polar reversal of the vertical displacement is rather located at west of MYGW. The new fault slip distribution fits well for all the stations at ground and offshore and provides new information on the earthquake generation process and on the kinematics of Northern Japan area.

1. Introduction

The growth of Japanese arc has been the result of the subduction process of the ancient Pacific Ocean floor since the Permian age. The actual shape is the outcome by the backarc basin formation in the Tertiary (Taira, 2001). Understanding the dynamic of the subduction processes is particularly important since it is principally along the plate boundaries that the seismic activity is concentrated. Monitoring these processes is also a valuable endeavor in tackling natural hazards and preventing risks for the population. The dense ground observations provide important data to monitor the crustal deformation and understand its process, including a dense GPS network of over 1000 stations and a dense seismic network with more than 1800 stations, together with many other crustal deformation measurement systems including InSAR, strong motion, teleseismic and tsunami detection systems.

At 05:46 UTC, 11 March 2011, a strong M_w 9.0 earthquake struck off the northeastern coast of Honshu, Japan. It was the strongest event in the seismic history of Japan and, for this reason, completely unexpected. Indeed, in terms of stress release, the catalogue of historical seismicity of Japan does not include a similar event. Moreover, no clear signal of preseismic tilt change or preslip was found (Hirose, 2011). A prediction of a $M \geqslant 8.0$ earthquake, with an intermediate-term (several years; usually five) narrow-range (areas of linear dimension 2–3 times the earthquake source zone size) accuracy, in the area of the M 9.0 Tohoku-Oki event, was made using a combined algorithm called M8-MSc (Davis et al., 2012). These pattern recognition methods are based on premonitory seismicity patterns and were designed by the retroactive analysis of seismicity preceding the greatest ($M \geqslant 8.0$) earthquakes worldwide (M8 method) or of the regional seismic catalogue prior to the Eureka earthquake (1980, $M = 7.2$) near Cape Mendocino in California (MSc method). The M8 method evaluates, every six months, the number of earthquakes (seismic flux rate), its

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deviation from long-term trend (differential of rate, i.e. acceleration), the linear concentration of sources and earthquake clustering. The algorithm MSc provides a second approximation to M8, and it is applied whenever the seismicity is sufficiently high to allow the algorithm to be used, strongly reducing the alarm area to a narrow or exact range. In particular, the MSc method evaluates the areas where seismicity is high but irregular, interrupted by short intervals of anomalous quiescence. See Davis et al. (2012) and the web site http://www.mitp.ru/en/, for more details. The prediction of a $M \geqslant 8.0$ earthquake was initially announced in mid-2001 and, successively, in January 2011, only 70 days before the Tohoku-Oki event, the algorithm detected a small change in the concentration of sources. It accurately identified the March 11, 2011, magnitude 9.0 Tohoku Earthquake, however it was not used, in part due to the predictions limited distribution and in part to the lack of applying existing methods for intermediate-term predictions which can be used to make decisions for taking actions.

Studies conducted using teleseismic ocean reverberations and applied to the first 4 s of the event (Chu et al., 2011) suggest that the Tohoku-Oki earthquake started as a small M_W 4.9 event and then evolved into a slower extremely large slip event up-dip. The Japan Meteorological Agency (hereafter JMA) reported the following hypocenter location: Lat 38.05°N, Long 142.8°E and depth 24 km (b.s.l.). The results of the CMT analysis indicates a reverse fault type mechanism with WNW–ESE compressional axis, in accordance with the direction of the Pacific Plate, which subducts under the Okhotsk Plate at a rate of about 8–9 cm/year (DeMets et al., 1990; Wei and Seno, 1998). The event was preceded by a M_W 7.3 foreshock (38.440°N, 142.840°E on 9 March 2011 at 02:45:20.28 UTC; USGS) and followed by more than 680 aftershocks estimated by the JMA.

The dynamic of this event has been widely investigated by many researchers, using different techniques (e.g., http://supersites.earthobservations.org/sendai.php). Most of these studies have focused on finite fault models by inversion procedures (Ide et al., 2011; Yoshida et al., 2011; Ozawa et al., 2011) or by Bayesian inference using a large number of forward models (Simons et al., 2011) in order to infer the location and size of the source. Despite the use of a large dataset, including GPS (on land and offshore) (Fujita et al., 2006; Sato et al., 2011; Kyriakopoulos et al., 2013), geological (Minoura et al., 2001), teleseismic (Chu et al., 2011; Zhang et al., 2011; Lay et al., 2011a), tsunami (Fujii et al., 2011), strong motion (Zahradnik et al., 2011), InSAR (Liu and Yamazaki, 2011) or combined techniques (e.g., Ammon et al., 2011; Koketsu et al., 2011; Yoshida et al., 2011; Yokota et al., 2011; Kobayashi et al., 2011; Gusman et al., 2012; Lee, 2012; Romano et al., 2012; Amici et al., 2013; Wang et al., 2013) the results are fairly different. Almost all studies, in fact, agree in describing the Tohoku-Oki earthquake as an M_W 9.0 event generated on a fault plane located at the interface between the Okhotsk Plate and the subducting Pacific Plate, but the inferred size, position (e.g., strike, dip and rake) as well as the way it ruptured and the maximum slip are not the same. Generally, the fault plane is inferred to have a strike angle between 192° and 202° and a fixed dip angle between 9° and 14°, although some authors consider also variable angles from 5° up to 20° (e.g., Yokota et al., 2011; Gusman et al., 2012).

The inferred size of the fault plane ranges between 300 km × 150 km (mainshock area) to 500 km × 250 km (including aftershocks area), while the maximum slip varies between 20 and 60 m. These differences are because inversion procedures strongly depend on the type and quality of the data used and on the rheological properties of the medium where the inversion is performed (e.g., homogeneous half-space versus a heterogeneous elastic medium).

In this paper, we use, as starting model, the solutions achieved by Caltech-JPL ARIA group and Geoazur CNRS (hereafter called "initial solution" provided by CJAGC), which give information on the area and displacement configuration of the fault plane. In particular, the inferred fault slip distribution allows to fit well the inland GPS recorded data. For this reason, we use the solution as a starting point for a new inversion, which includes both GPS and offshore data, performed through a numerical model based on the finite element method (hereafter, FEM). Results of inversion procedures can be in fact improved by using FEM because, under proper boundary conditions (which depend on the area of study), finite element models have the possibility of well approximating the geometry of the plates and of considering how the solution changes along each part of them as well as evaluating how the changes in the rheological properties or the presence of the topography affect the solution at the surface. Indeed, the finite element approach allows us to consider a more realistic approximation of the slip estimation by introducing both lateral and vertical variations of the elastic properties and the presence of topography (for other similar studies about large subduction earthquakes see, e.g., Trubienko et al., 2013).

As well known in literature (e.g., Cattin et al., 1999; Masterlark 2003; Aloisi et al., 2011; Hsu et al., 2011), the simple analytical model approach (homogeneous, isotropic, Poisson-solid half-space assumption) has in fact strong limitations and introduces significant displacement prediction errors (with respect to measurement uncertainties). In particular, Cattin et al. (1999) found that rigidity contrasts, existing within the upper crust can increase the horizontal displacements for a given slip model by up to 40%. Therefore, avoiding to take into account the effect of an existing low-rigidity layer leads to an underestimation of the seismic moment release and produces errors in the estimation of fault depth and slip from coseismic geodetic data. Masterlark (2003) asserts that the widely accepted homogeneous, isotropic, Poisson-solid half-space assumptions poorly approximate subduction zone systems of converging oceanic and continental crust. Hsu et al. (2011) affirms that topographic effects can be significant near a trench and slip distribution is strongly influenced by 3D variations of material properties, although the fit to surface observations in the 3D FEM model could be similar to that from a simple half-space model. Because of the related complexity, some of these aspects have been rarely implemented in previous studies.

2. Tectonic setting

The Japanese arc system is rather complex and related to the interaction of several plates. Five plates are generally identified: the Eurasia, Amur, Okhotsk, Pacific, and Philippine Sea plates but the exact shape and margin of these plates are still controversial (Heki et al., 1999; Jin et al., 2007; Zhao et al., 2011). The 11 March 2011 Tohoku Oki interplate earthquake, a M_W 9.0 event, struck at 05:46:23 UTC off the northeastern Japan coast, where the Pacific plate moves northwestward at a rate of about 8–9 cm/year, subducting beneath northern Honshu island from the Japan trench (Fig. 1).

3. Methods and data

In this section, the methods to develop our FEM model are described. As aforementioned, the finite fault inversion solution provided by CJAGC, called "initial solution", (http://www.tectonics.caltech.edu/slip_history/2011_taiheiyo-oki/#slip) is used as initial slip estimation to be optimized in our model. The "initial solution" is the result of the inversion of Global Seismographic Network broadband data and GPS data (Ji et al., 2002). The hypocentral location estimation was based on the JMA estimate (Lat 38.05°N, Long 142.8°E, depth 24 km, b.s.l.). The dip angle for the slab was taken from the National Earthquake Information Center (NEIC)