Earth and Planetary Science Letters 443 (2016) 118–128

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Improved source parameter constraints for five undersea earthquakes from north component of GRACE gravity and gravity gradient change measurements

Chunli Dai [a,*], C.K. Shum [a,d], Junyi Guo [a], Kun Shang [a], Byron Tapley [b], Rongjiang Wang [c]

[a] Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, OH, USA
[b] Center for Space Research, University of Texas at Austin, TX, USA
[c] Physics of Earthquakes and Volcanoes, GFZ German Research Centre for Geosciences, Potsdam, Germany
[d] State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China

ARTICLE INFO

Article history:
Received 28 September 2015
Received in revised form 5 March 2016
Accepted 12 March 2016
Available online 30 March 2016
Editor: P. Shearer

Keywords:
GRACE
north component
earthquakes
fault parameters

ABSTRACT

The innovative processing of Gravity Recovery And Climate Experiment (GRACE) data using only the north component of gravity change and its corresponding gravity gradient changes allows the enhancement of the spatial resolution for coseismic deformation signals. Here, we report the study of five undersea earthquakes using this technique: the 2004 Sumatra–Andaman earthquake, the 2007 Bengkulu earthquake, the 2010 Maule, Chile earthquake, the 2011 Tohoku earthquake, and the 2012 Indian Ocean earthquakes. By using the high spherical harmonic degree (up to degree 96) data products and the associated GRACE data processing techniques, the retrieved north component of gravity change is up to -34 ± 1.4 μGal for the 2004 Sumatra–Andaman earthquake, which illustrates by far the highest amplitude of the coseismic signal retrieved from satellite gravimetry among previous studies. We creatively apply the localized spectral analysis as an efficient method to empirically determine the practical spherical harmonic truncation degree. By combining least squares adjustment with the simulated annealing algorithm, point source parameters are estimated, which demonstrates the unique constraint on source model from GRACE data compared to other data sources. For the 2004 Sumatra–Andaman earthquake, GRACE data produce a shallower centroid depth (9.1 km), as compared to the depth (28.3 km) from GPS data. For the 2011 Tohoku earthquake, the GRACE-estimated centroid location is southwest of the GPS/seismic solutions, and the slip orientation is about 10° clockwise from the published GPS/seismic slip models. We concluded that these differences demonstrate the additional and critical offshore constraint by GRACE on source parameters, as compared to GPS/seismic data.

1. Introduction

The quantification of large undersea earthquakes, including their sizes, location, geometry and orientation of the faults, is critical for improving our understanding of fault mechanisms, and for applications in tsunami warning. As pointed out by Geist et al. (2007), the centroid location and seismic moment are the most essential parameters (Meng et al., 2012; Tanioka and Satake, 1996) for tsunami forecast and hazard assessment models; while other first-order source parameters such as dip, fault length and width also affect the tsunami wave field (Geist et al., 2007). Besides seismic data and GPS data, which are traditionally used for studying focal mechanisms, other data sets including the Interferometric Synthetic Aperture Radar (InSAR) data, tsunami data, and repeated airborne LiDAR data, have also been used. However, there are limitations for each type of data set on estimating the source parameters of undersea earthquakes.

Seismological methods have difficulty in estimating source parameters in some instances, e.g., seismic moment for ruptures with long duration due to the overlap of interfering arrivals (Chlieh et al., 2007; Lay et al., 2005), and seismic wave data are also inadequate for detecting slow or aseismic slip and postseismic slip (Chlieh et al., 2007; Han et al., 2013). One example for a long duration, slow rupture is the 2004 Sumatra–Andaman earthquake (Banerjee et al., 2005; Lay et al., 2005; Park et al., 2005), which also had large magnitude of afterslip (Chlieh et al., 2007). Lay et al. (2010) indicate that seismic inversions are sensitive to waveform types and the frequency band, which is shown by the fact that different slip models are obtained from seismic waves with

* Corresponding author.
E-mail address: dai.56@buckeyemail.osu.edu (C. Dai).

http://dx.doi.org/10.1016/j.epsl.2016.03.025

different frequency bands. In addition, since seismic inversions are highly dependent on the velocity structure, they have instabilities for shallow ruptures (Lay et al., 2011).

Although geodetic measurements, such as GPS data, have the potential to overcome the inadequacy of seismological data in detecting slow/aseismic slip, they are limited by the spatial distribution of their ground-based sites. Particularly, for undersea earthquakes, although more ocean-bottom measurements are available, GPS stations are mostly located at one side of the fault area, thus providing limited constraints on source parameters (Chlieh et al., 2007; Lay et al., 2011; Wei et al., 2012). For example, Chlieh et al. (2007) and Wei et al. (2012) showed that inland static GPS data are quite insensitive to shallow ruptures and resolutions of inverted slip models decrease rapidly away from the coast.

The twin-satellite Gravity Recovery And Climate Experiment (GRACE) mission (Tapley et al., 2004) has been producing temporal global gravity field observations with monthly sampling rate and a spatial resolution up to spherical harmonic degree 60. The GRACE data have revolutionized our understanding of Earth's mass redistribution, including terrestrial hydrologic water balance, ocean mass variations and sea level rise, and ice-sheet and glacier ablation, and their possible links with anthropogenic climate change. As one of such mass redistribution processes, earthquakes trigger crustal/mantle dilation or compression and surface uplift or subsidence, causing permanent change in Earth's gravity field. By surveying right above the rupture region over the ocean, although with a coarse spatial and temporal resolution, GRACE data have been demonstrated to have the feasibility to complement other data for detecting and constraining focal mechanisms of large undersea earthquakes, since GRACE data have a better spatial coverage as compared to GPS data, and have better capability to detect aseismic slip as compared to seismic data. Several large earthquakes have been detected in GRACE data and analyzed in contemporary studies, including the 2004 Sumatra–Andaman earthquake (e.g., Han et al., 2006; Wang et al., 2012c), 2010 Maule, Chile earthquake (e.g., Han et al., 2010; Heki and Matsuo, 2010; Wang et al., 2012a), and the 2011 Tohoku earthquake (e.g., Cambiotti and Sabadini, 2012; Dai et al., 2014; Han et al., 2011, 2013; Li and Shen, 2015; Matsuo and Heki, 2011; Wang et al., 2012b). Moreover, GRACE has also shown its unique contribution to the detection of postseismic gravity signals (Han et al., 2014; Panet et al., 2010; Tanaka and Heki, 2014).

Recent studies explored different data processing methods to better retrieve co- and postseismic gravity change signal from GRACE data. Wang et al. (2012c) showed a spatial resolution enhancement by using the inferred gravity gradient changes computed from GRACE temporal gravity field solutions, for the 2004 Sumatra–Andaman earthquake. To optimize the spatial and temporal resolution, Han et al. (2011) directly exploited the signal of the 2011 Tohoku earthquake in the change of inter-satellite K-band range (KBR) rate. Wang et al. (2012a, 2012b) for the first time utilized the Slepian functions (Simons et al., 2006) to analyze GRACE-observed gravity changes aiming at the spatial resolution enhancement of the coseismic signals. The same techniques are also applied for the source parameters inversion by Cambiotti and Sabadini (2012). Furthermore, an innovative approach of using only the north component of gravity change (Dai et al., 2014), the corresponding gravity gradient change, e.g., *Txx* and *Txz* (x, z refers to north and up directions, respectively) change by Wang et al. (2012c), *Txz* change by Li and Shen (2011), are found to substantially avoid the correlated errors in the GRACE temporal gravity field solution, with no decorrelation nor spatial filtering needed, leading to improved spatial resolution at the full wavelength corresponding to the highest spherical harmonic degree of GRACE data.

The inversion for several source parameters, such as the seismic moment, dip angle and rake angle, based on normal mode formulation assuming point dislocation were demonstrated for the 2011 Tohoku earthquake (Han et al., 2011). Wang et al. (2012a, 2012b) adopted the Markov Chain Monte Carlo algorithm to invert for fault length and width of the 2010 Chilean Maule and the 2011 Tohoku earthquakes, based on a finite fault model assuming uniform slip. Cambiotti and Sabadini (2013) presented an estimation of all fault parameters (centroid location and moment tensor) for a point source using GRACE data. Han et al. (2013) solved for the seismic moment tensors of multiple centroids, but with locations fixed, based on the normal mode formulation for a number of large earthquakes over the last decade using GRACE data. Dai et al. (2014) further solved for the centroid location, seismic moment, fault width, and slip rake angle based on finite fault model using simulated annealing algorithm, and found that GRACE data are especially effective in constraining centroid location and slip orientation.

In this paper, the new approach of GRACE data processing using only the *north* component of gravity change and the corresponding gravity gradient change (Dai et al., 2014) is adopted to detect the coseismic signal for five recent large undersea earthquakes using several different GRACE products, including particularly the high degree (up to degree 96) CSR RL05 data. By using the linear algorithm of gravity and gravity gradient change with respect to the double-couple moment tensor, the point source parameters are estimated through a least squares adjustment combined with the simulated annealing algorithm. From the improved GRACE data processing method, the high degree (up to degree 96) data products, and the new inversion scheme, we solve for the point source parameters for the 2004 Sumatra–Andaman (M_W 9.2) earthquake, the 2011 Tohoku (M_W 9.0) earthquake, the 2010 Maule, Chile (M_W 8.8) earthquake, the 2012 Indian Ocean (M_W 8.6 and M_W 8.2) earthquakes, and the 2007 Bengkulu (M_W 8.5) earthquake. The results show the resolving power of GRACE data on slip orientation, and centroid location and depth.

2. Improved GRACE data processing

This work is based on the GRACE data processing method of using only the *north* component of gravity and gravity gradient changes developed in Dai et al. (2014). To enhance spatial resolution, we further advance this approach by applying the localized spectral analysis as an efficient method to determine the practical spherical harmonic truncation degree from high degree L2 products. As an example, this localized spectral analysis suggests that only the degrees less than 70 from the high degree (up to 96) CSR L2 Release 05 (RL05) monthly geopotential solutions contain reliable seismic signal for the 2011 Tohoku earthquake as shown in the following paragraph.

The localized spectra analysis (Wieczorek and Simons, 2005) is used as an efficient method to justify the choice of practical truncation degree. Dai et al. (2014) show the application of this localized spectral analysis in the way of evaluating the signal and noise level of each component of gravity and gravity gradient as function of spherical harmonic degree. Here we compute the localized degree variance, and the results are shown in Fig. 1. Where, the north, east, and down components of the gravity disturbance are denoted by g_N, g_E and g_D, and the north components of gravity gradient disturbances are denoted by *Txx, Txy* and *Txz* (x, y, z, is north, west, up direction). The coseismic signal is estimated by fitting the GRACE-observed gravity and gravity gradient time series on a regular grid with a model composed of a Heaviside step function, a linear trend and three periodicities (equation A4, Fig. S1). We can see that the GRACE-observed g_N change (Fig. 1a) agrees well with the model prediction up until around degree 70, with slightly larger amplitude; while, the degree variance for GRACE-observed g_E and g_D change (Fig. 1a) increases sharply starting