Global co-seismic displacements caused by the 2004 Sumatra-Andaman earthquake (Mw 9.1)

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This paper presents and discusses the global co-seismic displacements caused by the 2004 Sumatra-Andaman earthquake, using quasi-static dislocation theory for a spherically symmetric earth model (Sun *et al*., 1996). Theoretical calculations are performed with a heterogeneous slip distribution fault model based on Ammon *et al*. (2005). Results show that the co-seismic horizontal displacements are large to the north-east and south-west of the fault plane. Even as far as 6000 km from the epicenter, more than 1 millimeter co-seismic horizontal displacements raised from the earthquake. This paper has three contributions: to validate the fault model (Ammon *et al*., 2005) by geodetic data; to interpret the displacements observed by GPS; and to provide a reference for other researchers or for other geodetic applications. Overall, the modelled and observed displacements basically agree with each other in both the near field and far field. The calculated displacements are a generally smaller than the observed ones, since considerable moment is released by slow-slips and/or aftershocks which has not been included in the fault model.

Key words: The 2004 Sumatra-Andaman earthquake, co-seismic displacement, dislocation theory.

1. Introduction

The 2004 Sumatra-Andaman earthquake occurred about 100 km off the west coast of the Northern Sumatra, and caused a devastating tsunami that hit coastlines across the Indian Ocean, killed about 310,000 people. In that area the relatively dense Indo-Australian plate moves beneath the lighter Burma plate with a relative velocity of about 6 cm/year (Khan and Gudmundsson, 2005). On 26 December 2004, however, the two plates moved several meters, releasing stress accumulated over hundreds of years.

It is well known that large earthquakes are accompanied by considerable crustal deformations around the epicenter. Before and after great earthquakes, significant co-seismic displacements have frequently been observed in the past decades, such as the Taiwan Chi-Chi earthquake (Mw 7.6) in 1999, the Kunlun earthquake (Mw 7.8) in 2001, and the Tokachi-Oki earthquake (Mw 8.0) in 2003. These observations indicate that the dominating deformations appear in the near field and attenuate rapidly as the epicentral distance increases. In a far field, say 1000 km distant from the epicenter, co-seismic displacements are usually difficult to detect. Thanks to the well-developed geodetic observation techniques and the extremely large seismic event, deformations caused by the Sumatra-Andaman earthquake have been detected clearly in the far field. For example, co-seismic strain steps were observed at Muzinami (35.4°N, 137.2°E) (Okubo *et al*., 2005) and Kamioka

(36.4°N, 137.3°E) (Araya, 2005)[1], in central Japan, about 5600 km from the epicenter. Also, co-seismic horizontal displacements were observed by GPS at distances of up to 4500 km from the epicenter (Banerjee *et al*., 2005). All these observations imply that co-seismic deformation accompanying the Sumatra-Andaman earthquake occurs not only near the epicenter, but over the whole earth. We attempt to investigate these global co-seismic displacements using both theoretical models and observations.

Dislocation theories in an elastic homogeneous half-space (Okada, 1985; Okubo, 1992) are widely used to evaluate the co-seismic deformation around the epicenter. However, they are not suitable to compute the co-seismic deformation in far field because the effects of the earth's curvature and layer structure must be taken into account. They can produce about 25% error if the layer structure is not considered (Sun and Okubo, 2002). A dislocation theory for a spherical earth is necessary to model the global co-seismic displacements and to interpret the observed ones. This study adopts the quasi-static dislocation theory of (Sun *et al*., 1996) for a spherically symmetric earth model to calculate global co-seismic displacements. For the Sumatra event, several new fault models with a heterogeneous slip distribution have been published (Yamanaka, 2004; Ammon *et al*., 2005; Banerjee *et al*., 2005; Vigny *et al*., 2005), which can serve as input for segment-summation scheme by (Fu and Sun, 2004). Based on spherical dislocation theory, global co-seismic displacements are then calculated for the fault model of (Ammon *et al*., 2005). Results of global co-

[1]Araya Akito, 2005. Strain Seismogram of the Sumatra-Andaman earthquake observed at crustal deformation station Kamioka (Personal discussion).
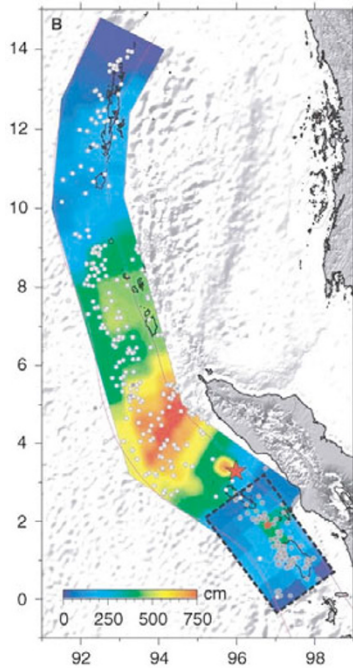
Fig. 1. Slip distribution of the 2004 Sumatra-Andaman earthquake according to Ammon *et al.* (2005). The surface projections of the fault segments are colored on the basis of the slip amplitude. Aftershocks are indicated by dots. Slip of the 28 March 2005 event is outlined with a dashed line. The red star marks the epicentre.
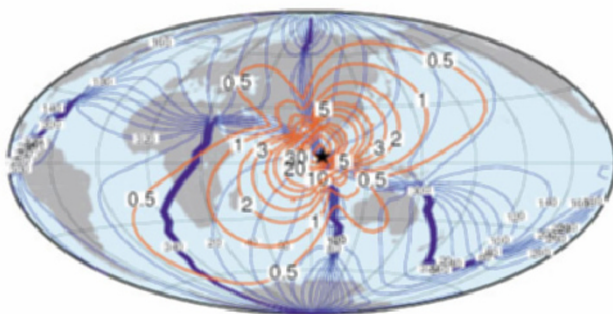

Fig. 2. Global horizontal displacements caused by the Sumatra-Andaman earthquake, as calculated by the spherical dislocation theory of (Sun *et al.*, 1996) and the seismic waveform inversion fault model of (Ammon *et al.*, 2005). The red lines show the contour of the amplitude of the horizontal displacements; blue lines indicate their directions. The dark star represents the epicenter. The unit is millimeters.
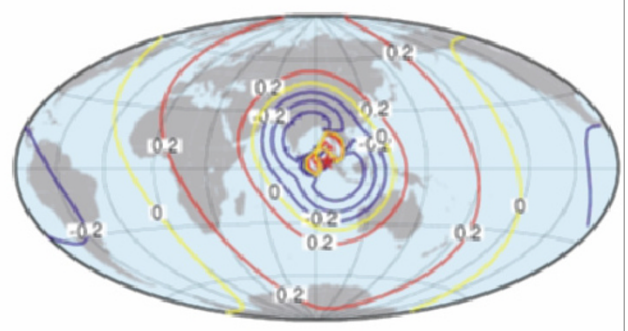

Fig. 3. Global vertical displacements caused by the Sumatra-Andaman earthquake. Red lines show the positive vertical displacements and the blue ones represent the negative ones. Yellow lines show the nodal line of the vertical displacement. The red star is the epicenter. The unit is millimeters.

Many different fault models for the 2004 Sumatra-Andaman earthquake have been obtained using different methods and data sources. Yamanaka (2004) computed a heterogeneous slip model soon after the earthquake by seismic waveform inversion. Banerjee *et al.* (2005) inverted three models from far-field static offsets. But due to the relatively high uncertainties of the far-field GPS data, as well as the sparse GPS station, the resolution of their models is insufficient to meet the need of this study. Vigny *et al.* (2005) inverted a fault model using 60 GPS data in the Southeast Asia. An unlikely feature of their model is that the largest slip is located at the deep edge of the fault. This might be caused by the improper use of the half-space dislocation theory (Okada, 1985), which can only properly evaluate the co-seismic displacements within 100 km epicentral distance. Ammon *et al.* (2005) computed three fault models by seismic waveform inversion. Their model B and C are the suitable choices for our study since the distribution pattern of the fault and the total moment (Mw = 9.1) are all acceptable. The models appear to be robust thanks to good data coverage.

We choose model B of Ammon *et al.* (2005) (Fig. 1) for this study. It was obtained by using a least-squares inversion of regional long-period seismograms in the period range from 100 to 3000 s and teleseismic waves in the period range from 80 to 300 s. The surface waves use the spherical Earth model corrections computed from the Harvard phase velocity model. The grid spacing is 50 km by 50 km. For each sub-fault, the dislocations are presumed to be equal; hence the segment-summation scheme (Fu and Sun, 2004) is directly applicable.

seismic displacements serve three purposes: to validate the fault model (Ammon *et al.*, 2005) by geodetic data; to interpret the displacements observed by GPS; and to provide a reference for other researchers who intend to investigate co-seismic deformations accompanying this seismic event, or for other geodetic applications: the inversion of the inter-structure, and post-seismic deformations to be observed in the future.

2. Fault Models of the 2004 Sumatra-Andaman Earthquake

In order to correctly reproduce the co-seismic displacements of the earthquake, we need to carefully choose the most suitable fault model.

3. Calculated Global Displacements Caused by the Sumatra-Andaman Earthquake

From the fault model, we compute the co-seismic displacements for the whole earth surface. The quasi-static dislocation theory for a spherically symmetric earth model (Sun *et al.*, 1996) is adopted for the computation. Note that the spherical dislocation theory is necessary for the present purpose because it contains both spherical curvature and layered effects, especially for far field computation. The displacement Green's functions presented in the theory of
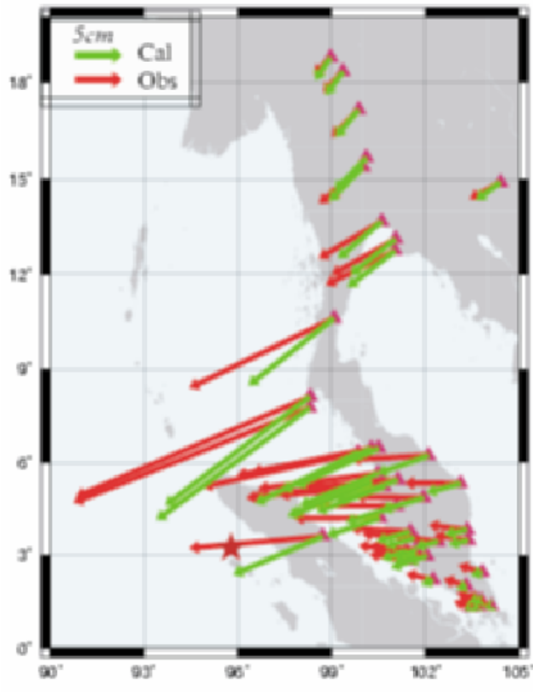
Fig. 4. Comparison of observed and calculated co-seismic displacements caused by the Sumatra-Andaman earthquake in the near field. The angles between the observed and calculated results indicate that there might be another big slip area on the north part of the model of Ammon *et al.* (2005), which are caused by the slow-slips and/or aftershocks.
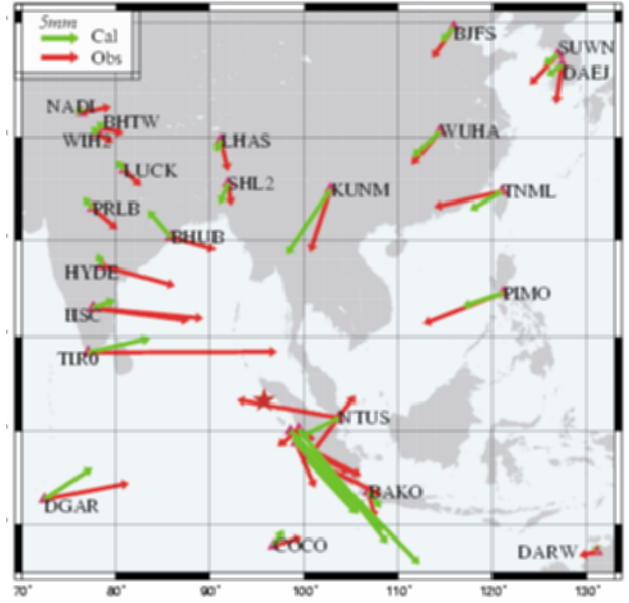

Fig. 5. Comparison of observed and calculated co-seismic displacements caused by the Sumatra-Andaman earthquake in the far field. Since the co-seismic displacements in far field are very small, the discrepancy between the observed and calculated displacements at most stations is still within the tolerance of the GPS observation.

(Sun *et al.*, 1996) are computed for a layered earth model, specifically symmetric model 1066A, with slight modification of the top layer to better fit the actual parameters around the epicenter. The displacement Green's functions are directly applicable to each cell of the above fault model, where a point source over each cell is assumed. Then the contribution to co-seismic displacement from each cell can be summed up using the segment-summation scheme (Fu and Sun, 2004). That is, the whole fault of the Sumatra-Andaman earthquake is divided into limited sub-faults, as given by the above fault model. Then the co-seismic displacements caused by each sub-fault are evaluated by applying point dislocation theory, and summing up the individual contribution over the whole sub-faults.

Global co-seismic displacements caused by this earthquake are calculated to investigate global distribution of the co-seismic displacements, and to determine whether or not the co-seismic displacements are detectable in the far field. Figures 2 and 3 respectively depict the global horizontal displacements and the vertical displacements. In Fig. 2, the red lines show the contour of the amplitude of the horizontal displacements; the blue lines indicate their directions. In the northeast and southwest areas, the co-seismic horizontal displacements are large. As far as 6000 km from the epicenter, more than 1 millimeter co-seismic horizontal displacements occurred during the earthquake. In the northeast and southwest, the directions of the horizontal displacements change smoothly. The concentrated blue contour lines give the nodal lines of the earthquake, near which the directions of the displacements are very sensitive. Small changes in observation location, as well as the fault model, result in

big changes in directions of the displacements.

Figure 3 shows the global vertical displacements resulted from the earthquake. Although the amplitudes of the vertical displacements are smaller than those of the horizontal displacements, the vertical displacements occur globally, even in North America, the furthest location from the epicenter. The distribution of the vertical displacements appears as a concentric-circle pattern around the epicenter. Red lines show the positive vertical displacement: blue lines indicate negative vertical displacements. The yellow lines are nodal lines of the positive and negative vertical displacements.

4. Comparison of Observed and Calculated Co-seismic Displacements

In this section we examine the actual crustal deformation observed by GPS to verify our modelled global co-seismic displacements in both the near field and far field. To the present, more than 100 geodetic observations have been presented (Vigny *et al.*, 2005; Banerjee *et al.*, 2005). Surface displacements at those stations are presented in Figs. 4 or 5 as red arrows. The calculated displacements at those sites are plotted as green arrows. Note that the fault model of Vigny *et al.* (2005) and Banerjee *et al.* (2005) were obtained using GPS data in Figs. 4 and 5, respectively. Hence it is natural that the consistency of the calculated and observed data in our study is worse than theirs.

Modelled and observed near-field displacements agree well, which verifies the validation of the fault model (Ammon *et al.*, 2005) and the theoretical displacements presented in Figs. 2 and 3. However, the calculated results are smaller than observations, meaning that considerable moment was released by slow-slips or by aftershocks, hence the total seismic moment is greater than Mw = 9.1, the

value given by Ammon *et al*. The angle differences between the observed and calculated results indicate that there might be another big slip area on the north part of the model, which are caused by the slow-slips and/or aftershocks.

As for the far field, it looks that the co-seismic displacements for some stations are underestimated. However, since the co-seismic displacements in far field are very small (millimetre order), the discrepancy between the observed and calculated displacements at most stations are still within the tolerance of the GPS observation. Therefore, the observed and calculated displacements can be considered to agree with each other. Specially, in the northeast and the southwest areas, the calculated and observed displacement directions coincide very well. However, there is no any agreement in directions between the observation and calculation in some stations, like BHUB, LUCK NADI and so on. The singular issue raised in the study, as well as that of Banerjee *et al*. (2005), is considered due to the high sensitivity of direction in nodal line of displacements, since slight changes in the fault model might change the directions of the displacements thoroughly at those stations.

Since the fault parameters inverted from seismic waveform data does not contain the information of slow-slips and aftershocks, it is reasonable that the calculated displacements are systematic smaller than the observed ones. Bedsides, the moment of the earthquake inverted from far field GPS data (Banerjee *et al*., 2005) are much bigger than those derived from near field GPS data (Vigny *et al*., 2005) and seismic waveform data (Ammon *et al*., 2005). This fact implies that there might exist small systematic errors in the procedures for the far field GPS data (Banerjee *et al*., 2005). In addition, the absolute displacements in the far field are so small that they deteriorate the effect of the small systematic error.

5. Discussions

In this study, the distribution pattern of the co-seismic displacements caused by Sumatra-Andaman earthquake are presented, as calculated using spherical dislocation theory (Sun *et al*., 1996), based on a layered spherical earth model (1066A), and a heterogeneous slip distribution fault model (Ammon *et al*., 2005) inverted from seismic waves. Results show that the Sumatra-Andaman earthquake generated considerable co-seismic displacements on the whole surface of the earth. As far as 6000 km from the epicenter, more than 1 mm co-seismic horizontal displacements occurred during the earthquake. The theoretical results presented in this research basically explain the observed co-seismic displacements. The results can serve as reference to study of inter-structure inversion, co-seismic deformation and post-seismic viscoelastic relaxation.

Comparisons between the calculated and observed displacements are then performed. Basically the calculated results agree with the observed ones, but generally smaller in far field. It implies that the seismic waves only derived fault model by Ammon *et al*. (2005) (Mw = 9.1) is not enough since considerable moment is released by slow-slip and /or aftershocks. Therefore, it might be much better and reasonable to produce a new model by combining seismic wave data and geodetic data (by GPS).

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