Analysis of Coseismic Fault Slip Models of the 2012 Indian Ocean Earthquake: Importance of GPS Data for Crustal Deformation Studies

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A b s t r a c t

Based on continuous GPS data, we analyze coseismic deformation due to the 2012 Indian Ocean earthquake. We use the available coseismic slip models of the 2012 earthquake, derived from geodetic and/or seismic waveform inversion, to calculate the coseismic displacements in the Andaman-Nicobar, Sumatra and Java. In our analysis, we employ a spherical, layered model of the Earth and we find that Java Island experienced coseismic displacements up to 8 mm, as also observed by our GPS network. Compared to coseismic offsets measured from GPS data, a coseismic slip model derived from multiple observations produced better results than a model based on a single type of observation.

Key words: the 2012 Indian Ocean earthquake, coseismic deformation, GPS displacement.

1. INTRODUCTION

On 11 April 2012, a M_w 8.6 Indian Ocean earthquake (IOE) occurred 300 km west of the Sunda trench (Meng *et al.* 2012). It was part of an earthquake sequence which involved a preshock of M_w 7.3 on 10 January 2012, a mainshock of M_w 8.6 on 11 April 2012, and an aftershock of M_w 8.2 two hours after the mainshock (Duputel *et al.* 2012). Considered to be the largest known strike-slip intraplate earthquake event, it has been suggested that the 2012 IOE occurred as a result of stress transfer after the 2004 M_w 9.2 Sumatra-Andaman earthquake and the 2005 M_w 8.7 Nias earthquake (Delescluse *et al.* 2012). The Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) reported that aftershock of $M > 3$ occurred practically continuously, with up to 400 events registered for six months after the 2012 IOE (Fig. 1).

Fig. 1. Tectonic background of this study. Beach balls represent earthquake occurrences offshore the western side of northern Sumatra over the last decade from the Global CMT catalogue. Black dots indicate six-month aftershocks of the 2012 IOE based on the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) catalogue.

Global Positioning System (GPS) data are an indispensable tool for analyzing the crustal deformation of the Earth. Previous crustal deformation studies, such as those of fault slip rate (Ito *et al.* 2012), fault coupling (Hanifa *et al.* 2014, Ohkura *et al.* 2015), coseismic and postseismic deformation (Gusman *et al.* 2015, Ito *et al.* 2016, Gunawan *et al.* 2016a, Alif *et al.* 2016), and aseismic slip after earthquake occurrences (Ardika *et al.* 2015, Raharja *et al.* 2016), inferring rheological models (Gunawan *et al.* 2014) and use of deformation for seismic hazard analysis (Meilano *et al.* 2015), have shown that GPS can be used comprehensively for crustal deformation analysis.

We utilize and compile all available GPS data sets associated with the coseismic deformation of the 2012 IOE, which have been previously reported in studies of Andaman-Nicobar (Yadav *et al.* 2013) and Sumatra (Feng *et al.* 2015). Also, we report additional GPS data from stations located in Java and along Sumatra that have not been reported so far.

Using these complete GPS sets, this study investigates the response of various available finite fault models of the 2012 IOE, namely by Hayes (http://earthquake.usgs.gov/earthquakes/eqinthenews/2012/usc000905e/finite_fault.php; accessed on December 2015), hereinafter referred to as the H12 model, by Yue *et al.* (2012), hereinafter referred to as the Y12 model; by Wei *et al.* (2013), hereinafter referred to as the W13 model; and by Hill *et al.* (2015), hereinafter referred to as the H15 model. We investigate how well these models fit to the observed coseismic offsets as derived from GPS data. Investigation of the best coseismic slip model is very crucial, especially in analyzing postseismic deformation after earthquake occurrences. In addition, understanding the distribution of coseismic slip during earthquake occurrences will greatly improve further hazard analysis.

2. COSEISMIC SLIP MODEL

Similar to other earthquakes of magnitude 8 or more, the 2012 M_w 8.6 IOE has attracted investigation of crustal deformation associated with this intra-plate earthquake. In order to invert the coseismic slip of the 2012 IOE, previous studies have used geodetic and/or seismic data. The H12 model used 38 teleseismic broadband P waveforms, 13 broadband SH waveforms, and 56 long-period surface waves to analyze the coseismic slip of the 2012 IOE. It was inferred that multiple faults were involved in the rupture. This suggested that a NNE-SSW fault plane with a strike of 199° and a WNW-ESE fault plane with a strike of 108° ruptured during this earthquake, with a maximum slip of 70 m (Fig. 2).

The Y12 model analyzed the 2012 IOE using short-period body waves and long-period surface waves recorded at teleseismic stations; it was suggested that rupture involved a very complex network of faults that had never

Fig. 2. Coseismic slip models of the 2012 IOE used in this study based on the results of Hayes (USGS), Yue *et al.* (2012), Wei *et al.* (2013), and Hill *et al.* (2015).

been documented or mapped before. They showed that the first fault, with WNW-ESE orientation, ruptured with seismic moment of $\sim M_w 8.5$, triggering the cross-cutting, orthogonal second fault in the NNE-SSW direction with seismic moment of $\sim M_w 7.9$. Then, the third fault in the direction of WNW-ESE ruptured with seismic moment of $\sim M_w 8.3$, at about 150 km southwest of the first fault. Finally, the fourth fault in the WNW-ESE direction, at about 330 km from the epicenter, ruptured with seismic moment of $\sim M_w 7.8$. The total rupture at these faults corresponds to a seismic moment of $\sim M_w 8.7$ (Fig. 2).

The W13 model analyzed coseismic slip of the 2012 IOE earthquakes using joint inversion of regional and teleseismic waveform data, showing

that the rupture started on an ESE-WNW fault with a strike of 289° , which produced a maximum slip of 12 m. Then, after 10 s, rupture continued on a 20° strike fault with maximum slip of 24 m. The third rupture occurred 70 s later, with a maximum slip of 8 m on a 310° strike fault. They showed that two hours after the mainshock, a $M_w 8.2$ earthquake occurred along a 16° strike fault with a maximum slip of 6.5 m (Fig. 2).

The H15 model used joint inversion of high-rate GPS data, far-field static GPS displacements, teleseismic observations and source time functions derived from broadband surface waves to analyze the 2012 IOE. They showed that most of the moment release was along the WNW-ESE right-lateral fault plane with a maximum slip of 48 m. Their result suggests that multiple faults ruptured during the event, including a NNE-SSW fault at 400 km west of the hypocenter (Fig. 2).

Because these studies used different methodologies and data, their results yield very different coseismic slip models. For example, the coseismic slip models of H12 and W13 considered the main rupture as occurring on a NNE-SSW fault, while the Y12 and H15 models considered the WNW-ESE fault to be the main rupture. Maximum slips obtained by these studies also differ, with the H12 coseismic fault model producing the highest maximum slip, followed by the H15, Y12, and W13 models.

3. GPS DATA AND METHOD

This study utilizes GPS data from stations surrounding the epicenter of the 2012 IOE, located in the Andaman-Nicobar region, Sumatra, and Java (Fig. 3). Some of these GPS data are obtained from previous studies, namely those reported by Yadav *et al.* (2013) and Feng *et al.* (2015). In addition to these available GPS data, we also use new GPS data sets from stations located in Sumatra and Java as part of the Indonesian Continuously Operating Reference Stations (InaCORS). Table 1 summarizes the GPS sites used in this study.

Yadav *et al.* (2013) reported the coseismic offsets of the 2012 IOE observed by the Andaman-Nicobar Permanent GPS Network (ANPGN). They showed that GPS sites in the Andaman Islands, which are located to the north of 2012 IOE, experienced southward movement with coseismic displacements up to 3 cm. The GPS site located at Nicobar Island experienced coseismic displacement of 4 cm in the southeast direction (Fig. 4).

GPS sites along Sumatra Island also experienced coseismic displacements during the 2012 IOE. Feng *et al.* (2015) pointed out that the SuGAR (Sumatran GPS Array) recorded significant offsets from the 2012 IOE, showing that Simeuleu Island experienced the largest coseismic offsets, up to 28 cm. The GPS network in northern Sumatra, named the Aceh GPS Net-

Fig. 3. Locations of GPS sites used in this study. Blue circles indicate GPS sites at Andaman-Nicobar from Yadav *et al.* (2013), black stars denote GPS sites of the SuGAR (Feng *et al.* 2015) and red hexagons and green squares represent GPS sites of BIG and IGS, respectively.

Table 1

Information about the GPS sites used in this study

Site	Long. [°]	Lat. [°]	Network	Site	Long. [°]	Lat. [°]	Network
ABGS	99.39	0.22	SuGAr ¹	MLBU	100.85	-1.81	InaCORS ²
BITI	97.81	1.08	SuGAr ¹	SAMP	98.71	3.62	InaCORS ²
BNON	96.15	2.52	SuGAr ¹	SEBL	101.60	-3.22	InaCORS ²
BSAT	100.28	-3.08	SuGAr ¹	SLBI	100.01	-2.77	InaCORS ²
BSIM	96.33	2.41	SuGAr ¹	TDAL	97.82	0.55	InaCORS ²
BTET	98.64	-1.28	SuGAr ¹	TIKU	99.94	-0.40	InaCORS ²
BTHL	97.71	0.57	SuGAr ¹	TLOK	100.50	-1.30	InaCORS ²
BUKT	100.32	-0.20	SuGAr ¹	TNBL	98.50	-0.53	InaCORS ²
HNKO	97.34	0.87	SuGAr ¹	CBAY	93.93	7.05	ANPGN ³
JMBI	103.52	-1.62	SuGAr ¹	HBAY	92.57	10.69	ANPGN ³
KTET	99.84	-2.36	SuGAr ¹	PORT	92.73	11.63	ANPGN ³
LAIS	102.03	-3.53	SuGAr ¹	HAVE	92.99	12.03	ANPGN ³
LEWK	95.80	2.92	SuGAr ¹	MBDR	92.90	12.90	ANPGN ³
LHW2	97.17	1.39	SuGAr ¹	PALK	80.70	7.27	IGS ³
LNNG	101.16	-2.29	SuGAr ¹	COCO	96.83	12.18	IGS ³
MKMK	101.09	-2.54	SuGAr ¹	BAKO	106.84	6.49	IGS ³
MLKN	102.28	-5.35	SuGAr ¹	XMIS	105.68	10.45	IGS ³
MNNA	102.89	-4.45	SuGAr ¹	CUSV	100.53	13.74	IGS ³
MSAI	99.09	-1.33	SuGAr ¹	DGAR	72.37	7.26	IGS ³
NGNG	99.27	-1.80	SuGAr ¹	CANG	107.52	-7.02	InaCORS ²
NTUS	103.67	1.346	IGS ¹	CBTU	107.10	-6.31	InaCORS ²
PARY	100.32	-0.75	SuGAr ¹	CCIR	108.56	-6.72	InaCORS ²
PBJO	98.52	-0.64	SuGAr ¹	CCLP	109.01	-7.74	InaCORS ²
PBLI	97.41	2.31	SuGAr ¹	CGON	106.05	-6.02	InaCORS ²
PKRT	99.54	-2.15	SuGAr ¹	CJKT	106.88	-6.11	InaCORS ²
PPNJ	99.60	-1.99	SuGAr ¹	CJPR	110.67	-6.60	InaCORS ²
PRKB	100.40	-2.97	SuGAr ¹	CJUR	107.14	-6.82	InaCORS ²
PSKI	100.35	-1.12	SuGAr ¹	CLBG	107.62	-6.82	InaCORS ²
PSMK	97.86	-0.09	SuGAr ¹	CMIS	108.34	-7.33	InaCORS ²
PTLO	98.28	-0.05	SuGAr ¹	CMLP	106.02	-6.78	InaCORS ²
SLBU	100.01	-2.77	SuGAr ¹	CPBL	109.36	-7.39	InaCORS ²
SMGY	100.10	-2.61	SuGAr ¹	CPKL	109.67	-6.89	InaCORS ²
TLLU	99.13	-1.80	SuGAr ¹	CPSR	105.83	-6.23	InaCORS ²

to be continued

Table 1 (continuation)

Site	Long. [°]	Lat. [°]	Network	Site	Long. [°]	Lat. [°]	Network
TRTK	100.62	−1.52	SuGAR ¹	CPTU	106.55	−6.99	InaCORS ²
UMLH	95.34	5.05	SuGAR ¹	CPWK	107.44	−6.55	InaCORS ²
CAIR	99.39	0.21	InaCORS ²	CRKS	106.25	−6.36	InaCORS ²
CBKL	102.27	−3.80	InaCORS ²	CROL	107.98	−6.31	InaCORS ²
CBKT	100.37	−0.31	InaCORS ²	CRUT	107.90	−7.22	InaCORS ²
CPDG	100.36	−0.95	InaCORS ²	CSUM	107.92	−6.86	InaCORS ²
CSAB	95.32	5.89	InaCORS ²	CTAN	107.12	−7.27	InaCORS ²
CTCN	104.73	−5.91	InaCORS ²	CTGL	109.14	−6.87	InaCORS ²
LHMI	96.95	5.23	InaCORS ²	JOGS	110.29	−7.82	InaCORS ²
MEGO	101.03	−4.01	InaCORS ²	HYDE	17.42	78.55	IGS ²
MEUL	96.13	4.13	InaCORS ²	IISC	13.02	77.57	IGS ²

¹Feng *et al.* (2015)

²This study

³Yadav *et al.* (2013)

work for the Sumatran fault System (AGNeSS; Tabei *et al.* 2015), was also affected by the 2012 IOE (Anugrah *et al.* 2015; Fig. 4).

In addition to the published data sets described above, we use the GPS network in Java and Sumatra installed and maintained by the Geospatial Information Agency of Indonesia (BIG). To analyze the daily coordinate solutions from these GPS sites, we use the GAMIT/GLOBK software package (Herring *et al.* 2010a,b). We process these GPS data together with several International GNSS Service (IGS) sites – DGAR, HYDE, IISC, COCO, XMIS, CUSV, KUNM, PIMO, GUAM, DARW, TOW2, KARR, TNML, and YAR2 – and tied the solutions into the International Terrestrial Reference Frame (ITRF) 2008 (Altamimi *et al.* 2011).

Our analysis indicates that GPS sites in Java experienced coseismic displacements up to 8 mm in the northwest direction (Fig. 4). The standard deviation obtained in our solution for each GPS site was about 4 mm. Table 2 summarizes the coseismic displacements from the 2012 IOE at the GPS sites used in this study.

Using the available coseismic slip models – H12, Y12, W13, and H15 – we calculate the modeled surface coseismic displacements based on a spherical, layered model of the Earth (Pollitz 1996) with elastic thickness of 65 km and Maxwell viscosity of 8.0×10^{18} Pa·s (Gunawan *et al.* 2014). Modeled surface displacements calculated using the coseismic slip models H12, Y12, W13, and H15 are compared to the observed displacements from

Fig. 4. Modeled displacements (gray arrows) calculated using the coseismic slip model of Hill *et al.* (2015) and observed coseismic displacements of the 2012 IOE at (a) northern Sumatra, indicated by blue arrows; (b) southern Sumatra, indicated by red arrows; (c) Andaman-Nicobar, indicated by green arrows; and (d) Java, indicated by black arrows.

Table 2

Coseismic displacements of the 2012 IOE at GPS sites

Site	E [mm]	N [mm]	σ_E	σ_N	Site	E [mm]	N [mm]	σ_E	σ_N
ABGS	9.8	12.0	1.6	0.7	MLBU	-4.1	9.7	4.8	3.9
BITI	40.0	22.3	1.5	0.4	SAMP	74.4	26.5	2.5	1.9
BNON	214.4	81.6	0.8	0.5	SEBL	-13.2	9.6	3.2	2.5
BSAT	-16.9	17.1	0.4	0.3	SLBI	-16.4	15.8	3.2	2.3
BSIM	185.6	68.4	0.9	0.5	TDAL	24.4	23.3	2.5	1.9
BTET	-21.3	24.7	0.4	0.4	TIKU	5.7	8.8	3.9	2.8
BTHL	24.7	24.8	0.5	0.3	TLOK	-2.5	7.5	4.5	3.1
BUKT	2.7	8.6	2.2	0.6	TNBL	-3.0	26.3	2.2	3.8
HNKO	40.9	31.5	0.6	0.5	CBAY	37.5	-17.8	6.2	5.6
JMBI	0.9	2.5	0.3	0.2	HBAY	2.9	-29.4	4.3	4.0
KTET	-20.3	17.1	0.4	0.4	PORT	2.4	-25.7	4.2	4.0
LAIS	-12.6	10.6	0.3	0.2	HAVE	1.8	-16.6	4.4	4.0
LEWK	262.8	117.4	1.0	0.5	MBDR	-0.5	-18.3	4.1	3.7
LHW2	68.6	32.5	0.9	0.8	PALK	-0.5	-4.9	4.0	3.6
LNNG	-11.0	9.7	0.3	0.2	COCO	-4.9	16.1	4.2	3.8
MKMK	-12.2	11.1	0.3	0.3	BAKO	-4.2	1.8	4.6	4.0
MLKN	-10.9	10.3	0.3	0.3	XMIS	-4.4	5.1	4.1	3.8
MNNA	-10.6	10.6	0.2	0.2	CUSV	3.4	5.0	4.4	4.0
MSAI	-18.8	20.0	0.3	0.2	DGAR	-10.3	-5.3	4.7	4.1
NGNG	-19.9	20.9	0.4	0.3	CANG	-5.0	3.1	3.7	2.6
NTUS	16.0	3.4	0.2	0.2	CBTU	-3.5	2.2	2.9	2.0
PARY	0.5	10.0	0.4	0.3	CCIR	-1.1	-0.3	3.3	2.2
PBJO	-8.4	20.7	0.4	0.3	CCLP	-2.0	-1.6	5.1	3.3
PBLI	108.5	35.3	0.6	0.4	CGON	-2.3	2.7	2.9	2.0
PKRT	-20.0	19.6	0.3	0.3	CJKT	-3.0	1.9	2.6	1.8
PPNJ	-19.7	19.3	0.3	0.3	CJPR	-1.2	3.1	5.4	3.4
PRKB	-24.1	21.8	0.4	0.4	CJUR	-7.1	-0.8	6.9	4.3
PSKI	-2.6	10.3	0.3	0.3	CLBG	-4.0	2.7	3.7	2.7
PSMK	0.1	28.1	0.3	0.3	CMIS	-8.4	-1.8	4.3	2.9
PTLO	5.1	22.8	0.3	0.3	CMLP	-3.3	3.9	4.4	3.0
SLBU	-19.2	16.5	0.4	0.3	CPBL	-0.5	0.3	4.2	3.1
SMGY	-17.0	17.6	0.4	0.3	CPKL	-3.2	0.7	3.9	2.8
TLLU	-19.3	23.2	0.3	0.3	CPSR	-2.6	5.2	3.7	2.6

to be continued

Table 2 (continuation)

Site	E [mm]	N [mm]	σ_E	σ_N	Site	E [mm]	N [mm]	σ_E	σ_N
TRTK	−6.6	9.5	0.3	0.3	CPTU	−2.8	1.7	4.6	3.1
UMLH	141.1	90.0	0.7	0.8	CPWK	2.2	1.7	2.9	2.0
CAIR	12.6	9.9	3.4	2.4	CRKS	3.2	7.4	4.6	3.0
CBKL	−10.9	9.5	3.9	2.2	CROL	−0.6	−0.1	2.9	2.0
CBKT	4.9	5.2	4.1	3.1	CRUT	−3.2	6.0	5.4	3.5
CPDG	−1.6	8.9	2.8	2.1	CSUM	−3.3	3.2	4.3	2.9
CSAB	87.9	59.8	3.2	2.5	CTAN	−1.9	1.9	5.0	3.2
CTCN	−6.5	4.9	3.0	2.0	CTGL	−3.2	−1.0	3.8	2.7
LHMI	98.5	64.9	2.6	1.9	JOGS	−1.5	−0.1	3.4	2.5
MEGO	−5.6	11.0	5.8	3.6	HYDE	2.1	−7.8	2.8	2.3
MEUL	175.6	97.3	2.5	1.9	IISC	3.3	−4.8	2.1	1.6

Table 3

Misfit of data displacements to model

Coseismic slip source	Data used for inversion	RMS
Hayes (USGS)	Seismic	28.10
Yue <i>et al.</i> (2012)	Seismic	20.51
Wei <i>et al.</i> (2013)	Seismic	17.47
Hill <i>et al.</i> (2015)	GPS + seismic	12.33

the GPS sites. We calculate the root mean square (RMS) between modeled and observed displacements to find the optimum coseismic model (Table 3).

4. DISCUSSION

Our study employs a spherical Earth model to calculate surface displacements at each GPS site. Other studies applied an elastic half-space model (Okada 1992), because it is much faster in terms of required calculation time (Piersanti *et al.* 1997). Unfortunately, the half-space model has limitations in areas far from the source, as the sphericity of the Earth starts playing role. To check the impact of using a half-space model for the far field region in Java, we calculate the H15 model using an elastic half-space model, yielding RMS of 22.17, a much higher misfit than that resulting from using spherical Earth analysis (RMS = 12.33). This indicates that using a spherical Earth model to analyze far field deformation is much more appropriate than using a half-space model.

This study suggests that the H15 model generates smaller misfit than the other models (Table 3), most likely because the H15 model uses joint inversion of seismic and geodetic data, while the other considered models use seismic data only. In another earthquake case, such as that of the 2004 Sumatra-Andaman earthquake, Poisson *et al.* (2011) showed that a coseismic slip model derived from geodetic data better explains the recorded tsunami observed by satellite altimetry than a coseismic slip model derived from geological observation, tide gauge records, or other data.

In another example, considering the 2006 Java tsunami earthquake, Gunawan *et al.* (2016b) suggested that the coseismic fault slip model obtained from tsunami data better agrees with the postseismic deformation observed by GPS than with the other models obtained from seismic data. Although only one GPS site (BAKO), located at a remote distance, was active during the 2006 Java tsunami earthquake, modeled coseismic displacements from data BAKO detected during the 2006 event were about 2.5 mm, which fits to the tsunami data better than the other models.

To summarize our investigation of the 2012 Indian Ocean earthquake, we showed that analysis of coseismic slip during earthquake occurrences obtained from a single type of observation, namely seismic data, poorly fits the GPS measurements. Similar results have been found in various other studies which only use seismic data with coseismic slip models, such as the study of the 2004 Sumatra-Andaman earthquake by Poisson *et al.* (2011). Instead, using multiple observations, such as seismic, geodetic, or tsunami data, as also shown by Hill *et al.* (2015) and Rhie *et al.* (2007), generates better results than using a single type of observation.

5. CONCLUSIONS

We analyzed the coseismic slip of the 2012 Indian Ocean earthquake based on the H12, Y12, W13, and H15 models. We used coseismic offsets obtained from GPS measurements in Andaman-Nicobar, Sumatra and Java, comparing these offsets to the modeled coseismic displacements from the available slip models using a spherical, layered model of the Earth. We find that Java Island experienced coseismic deformation of up to 8 mm, as observed by our GPS network. Our results suggest that a coseismic slip model obtained from multiple observations of seismic and geodetic data – the H15 model – produced less misfit than the coseismic slip models obtained using a single type of observation (from a seismic network).

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