Learning a Disaster from Earthquake Cycle Deformation (Case Study Jogjakarta Earthquake with the LUSI Eruption 2006)

Heri ANDREAS, Dina A. SARSITO, Hasanuddin Zainal ABIDIN, Irwan MEILANO, Indonesia

Key words : Earthquake cycle, Deformation, disaster, Mitigation

SUMMARY

Base on empirical data it is no doubt that earthquake can be re-occur from the past, it called earthquake cycle. In between the cycle we have known the interseismic, preseismic, coseismic, and postseismic events. One best way to see the events is through deformation measurements. At the inter-seismic sequence, the two plates interface is locked by friction. The upper plate is accumulating elastic deformation at a slow rate (~1cm/yr). This loading phase can last for centuries. At the coseismic sequence, the earthquake releases in one moment deformation accumulated for centuries. At that stage, the upper plate “rebounds”. In the subduction zone, the whole system being below sea level, this giant “kick” in sea water generates a tsunami. At the post-seismic sequence, Return to equilibrium and steady loading deformation can take years. From these measurements, particularly on coseismic and postseismic events we may calculate stress transfer that would be useful for next hazard evaluation as well as mitigation.

We did the measurements over Jogjakarta earthquake coseismic event in 2006 using the GPS, and calculate static and dynamic stress produce by this earthquake. Two days followed the event there was mud volcano (LUSI) eruption 250 km east away. The eruption base on some argument suggested derived from interseismic sequence event of Watukosek fault (crossed the eruption vent) entering the coseismic sequence event triggered by Jogjakarta earthquake. As coincidence we measure GPS repeatedly around the LUSI area as well as Jogjakarta as mentioned earlier, so in this case we can see clearly both deformations pattern and magnitude, and how the two disasters may related. We can learn from them (including commented the argument) and for sure for hazard evaluation and mitigation.

Learning a Disaster from Earthquake Cycle Deformation (Case Study Jogjakarta Earthquake with the LUSI Eruption 2006)

Heri ANDREAS, Dina A. SARSITO, Hasanuddin Zainal ABIDIN, Irwan MEILANO, Indonesia

1. EARTHQUAKE CYCLE DEFORMATION

Until today, the mantle convection still believed as an appropriated theory to explain the movement of the plates and the source mechanism of the earthquake. The energy from convection steering the plate to move one another. One block of plates and the others would converge, diverge, or move side by side. At the plates interface where two plates merge and locked by friction, then this earth's crust area will experienced a deformation. As the energy from the mantel will continuously forced the plates to move consistently, a consequences the deformation in the plates interface will increasingly accumulated. Within few ten years to hundred years when the accumulation of deformation reached maximum stage, this earth's crust may fails in response to those accumulated deformation and produce the sudden breaking and shifting of large sections of the earth's crust, making the ground to shake and its called earthquake.

For a moments, the energy was released by the earthquake (mainshock and aftershock), made the deformation return to zero. The earthquake has unlock the friction. But after few months to few years when this dynamic earth has return to equilibrium stage, the plates interface will experienced new deformation. Again, the merged plates could lock by the friction and the deformation will beginning to accumulated leading to failure respond of this earth's crust producing new earthquake. This sequence called earthquake cycles. In detail the earthquake cycles divided into inter-seismic, co-seismic, and post-seismic sequence (fig 1). Pre-seismic is now still being analyzed before officially included as part of all sequence.

inter-seismic

At the inter-seismic sequence, the two plates interface is locked by friction. The upper plate is accumulating elastic deformation at a slow rate (~1cm/yr). This loading phase can last for centuries

Co-seismic

The earthquake releases in one moment deformation accumulated for centuries. At that stage, the upper plate "rebounds". In the subduction zone, the whole system being below sea level, this giant "kick" in sea water generates a Tsunami

Post-seismic

Return to equilibrium and steady loading can take years.

Geodetic measurement (e.g. GPS and InSAR) with space and time domain (continuous or periodic) may detected those ground deformation as well as the accumulation of them. Geodetic measurement may also constrains physical model of the processes that cause earthquake event [Hudnut et.al 1994]. With geodetic measurement we may saw clearly inter-seismic phase of earthquake mechanism, pre-seismic signal also sometimes recorded, and well recorded co-seismic and post-seismic signals. Inter-seismic pattern is now being included as one of parameter in estimation the probability of earthquake hazard.

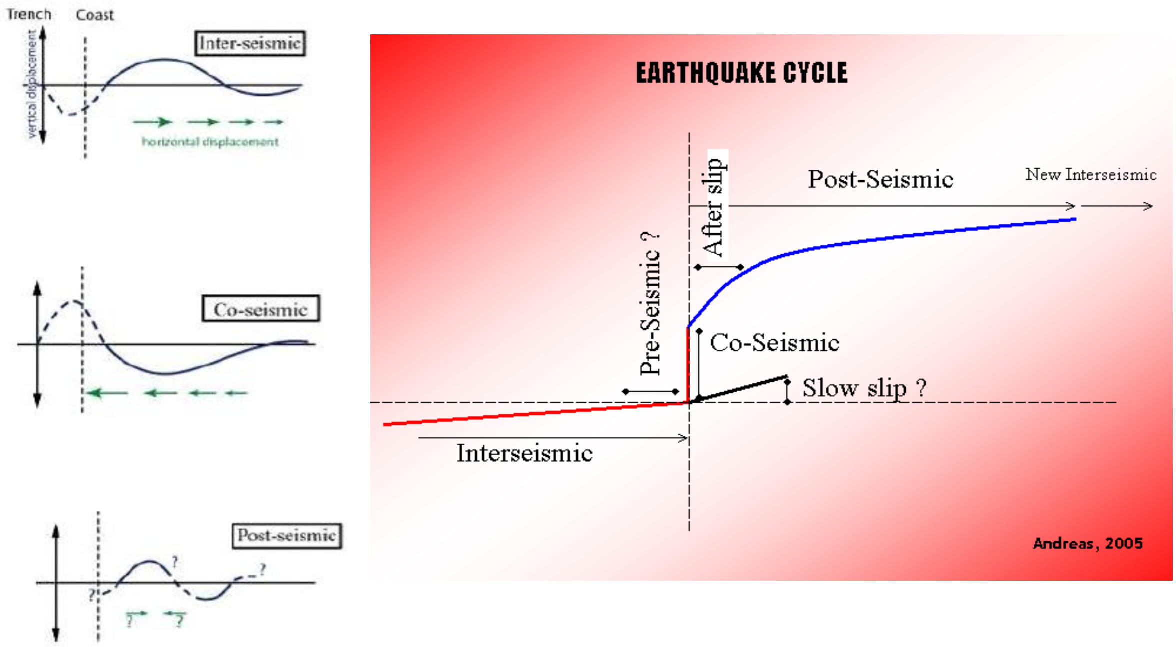

Figure 1 Earthquake cycle divided into inter-seismic, pre-seismic, co-seismic, and post-seismic sequence, including slow slip event.

Detection of slow inter-seismic strain accumulation is probably the best technique we have for identifying the location of future earthquakes in some areas, because elastic rebound requires elastic strain accumulation prior to earthquakes. Well recorded co-seismic deformations can be related to the earthquake source process. Further on this records can thus be inverted to determine the geometry of earthquake rupture(s). Once we found the geometry of the rupture it help us for better understanding the co-seismic mechanism and the stress transfer mechanism concerning the evaluation to the next earthquake potential occurrence and the constrain of predicted area. Well recorded post-seismic deformations has shown fact that the energy of an earthquake would never reached a hundred percent by the mainshock, in some cased shown only fifty percent released by the mainshock while post-seismic hold the rest and release them in long period time intervals.

2. JOGJAKARTA EARTHQUAKE

Jogjakarta and it surrounding was struck by the Earthquake on May 27, 2006. The earthquake occurred at 5:54 a.m. local time (22:54 GMT 26 May), with its epicenter estimated around 25 km (15 miles) south-southwest of the Indonesian city of Jogjakarta, near Galur, on the southern side of the island of Java (8.007° S 110.286° E), 17.1 km below the seabed, according to the U.S. Geological Survey. The USGS-estimated magnitude of first earthquake is Mw 6.3. Subsequently, about 750 aftershocks have been reported, with the largest intensity recorded at Mw 5.2

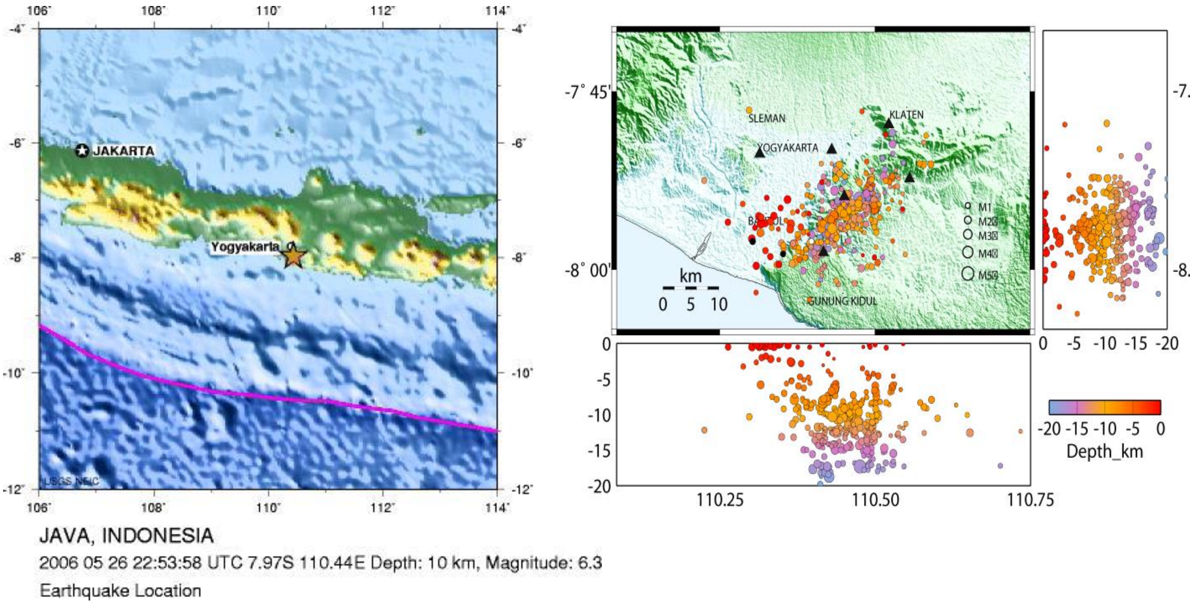

Figure 2 The Jogjakarta earthquake epicenter and aftershock

According to USGS (United State Geological Survey), the tectonics of Java is dominated by the subduction of the Australia plate north-northeastward beneath the Sunda plate with a relative velocity of about 6 cm/year. The Australia plate dips north-northeastward from the Java trench, attaining depths of 100-200 km beneath the island of Java, and depths of 600 km north of the island. The earthquake of 26 May 2006 occurred at shallow depth in the overriding Sunda plate well above the dipping Australia plate. The earthquake is believed to be caused by the movement of Opak fault. The earthquake is thought to have been tectonic in origin and not directly associated with the ongoing eruption of nearby Mount Merapi, although the earthquake is reported to have caused increased activity in the volcano.

According to the official report, there have been 6,234 deaths, while 36,299 people have been injured, 135,000 houses damaged, and an estimated 1.5 million left homeless. 3,580 of those deaths and more than 1,892 injuries occurred in the area of Bantul, while 1,668 others died in Klaten district. Around five million people live within 50 km of the epicenter.

A week after the earthquake, namely 4 to 8 June 2006, GPS surveys were conducted on 48 GPS points belonging to the 2nd order GPS network around Jogyakarta and Central Java, that was firstly observed in 1998 (fig 3). GPS surveys were conducted using 14 geodetic-type dual-frequency GPS receivers. Each of GPS point is observed for about 8 to 10 hours, while the reference point located in UGM Boulevard Jogjakarta is observed continuously. The observation is carried out with 30 second data interval and mask angle of 15^0. The example of some GPS stations is shown in the figure. GPS data processing is done using scientific processing software Bernese 4.2.

GPS results show that horizontal co-seismic displacement around Bantul and Jogjakarta are mostly less than 10 cm, with mostly south and south-west directions. Derived GPS displacements indicated the existence of left-lateral fault. These GPS displacements indicate that this fault is located in the east of Opak fault indicated in the geology map. The calculated static stress influences 30 km2, while dynamic stress value is 21 +33/-12 kPa.

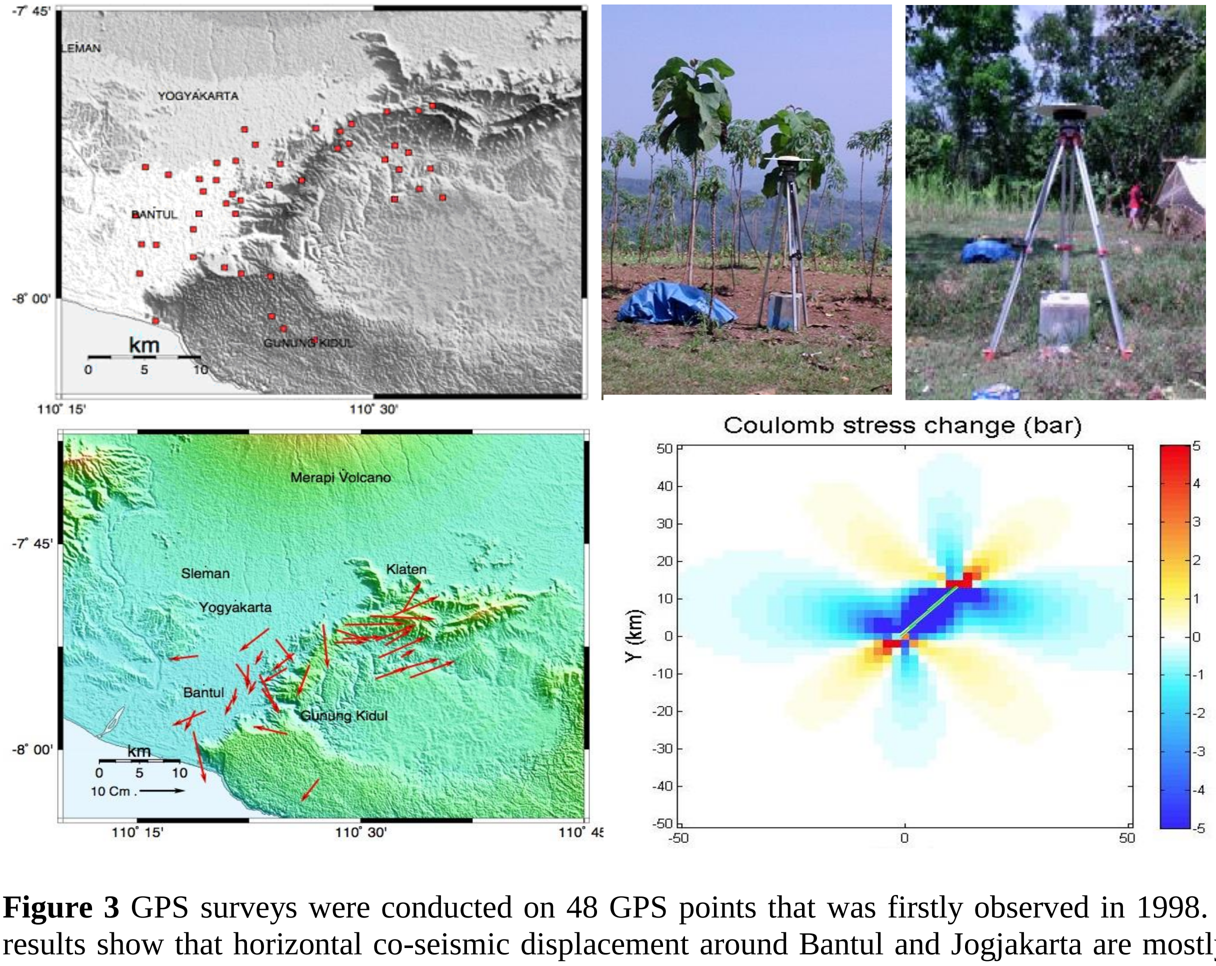

Figure 3 GPS surveys were conducted on 48 GPS points that was firstly observed in 1998. GPS results show that horizontal co-seismic displacement around Bantul and Jogjakarta are mostly less than 10 cm, with mostly south and south-west directions. The static stress influences 30 km2 and dynamic stress value is 21 +33/-12 kPa.

3. LUSI MUD VOLCANO

On May 29, 2006 a mud volcano started to form at Porong Sidoarjo East of Java Indonesia. It is further termed as LUSI Mud Volcano (LUSI = Lumpur Sidoarjo ; Lumpur mean mud in Indonesia language). Mud, Water, and Gas extruded masively and flooding more than a kilometer areas. Since its extrusion day, the mud mixed water and gas has caused significant livelihood, environmental and infrastructure damage (Fig 4b,c,d). The volumes of erupted mud increased from the initial 5000 m^3/day in the early stage to 120,000 m^3/day in August 2006. Peaks of 160,000 and 170,000 m^3/day of erupted material follow earthquakes swarms during September 2006; in December 2006 the flux reached the record-high level of 180,000 m^3/day; and in June 2007 the mud volcano was still expelling more than 110,000 m^3/day (Manzini *et al.*, 2007).

Figure 4 (A) LUSI mud volcano eruption, (B) crack on the floor, (C) crack on the ground around relied well-1, (D) crack on the house in Sengon Village

Considering the effects of mud loading, collapse of the overburden due to the removal of mud from the subsurface and, land settlement caused by surface works (e.g. construction of dykes), etc., ground displacements occurred. Latter on, the surface representation of displacement was also occurred such as crack on the wall, houses, street, bend on the rail ways, etc.

GPS observations, both in campaign and continuous mode were conducted to study ground displacement phenomenon that following the birth and development of LUSI mud volcano. Fivetheen GPS campaigns have been conducted between June 2006 and May 2011. Bellow (fig 5) we can see some documentation of GPS survey in the field.

Figure 5 Some documentation of GPS survey in the field using dual-frequency geodetic-type receivers, with observation session length of about 5-10 hours

GPS surveys were performed on up to about 50 stations with set area over 10 kilometers rounding the center of eruption, using dual-frequency geodetic-type receivers, with observation session lengths of about 5-10 hours. GPS continuous subsidence monitoring was also conducted on some stations, started on 22 September 2006 to early 2007. Due to the change in mud coverage area, the numbers of observed GPS stations were different from survey to survey, and the observed stations could not always be the same. The locations of GPS stations were also restricted by the mud coverage and its progression. Data processing of the GPS survey data was conducted using the scientific GPS processing software Bernese 4.2 (Beutler et al., 2001). In general, standard deviations of the estimated coordinates are of the order of several mm in both horizontal and vertical components. To derive the ground displacement information is simply by differencing the coordinates that has processed in each period of GPS surveys.

Tables 1 present magnitude of subsidence for 1, 2, and 4 years since the LUSI eruption started. In the tables we can see the GPS monitoring stations arranged in a distance from the eruption. In this case, we can do the spatial analysis on how far the eruption effected the deformation, how is the magnitude related to the distance from eruption, etc. While other researchers focused on the vertical component of deformation or subsidence (e.g. Abidin *et al*., 2008, Fukushima *et al*., 2009), we consider here both vertical and horizontal components. Table 2 shows results for horizontal components.

In order to interpret the ground deformation around LUSI mud volcano, we divided the measurements into spatial domains corresponding to inside the caldera, near the rim of the caldera, and outside the caldera (Davies *et al*., 2007, 2010). Our data distinguished different characteristics of deformation among those spatial domains. Deformation inside the caldera is associate with caldera formation processes and is characterized by rapid subsidence, while the rim and outside caldera have normal rates of subsidence (Andreas *et al.*, 2010) which are most probably (Abidin *et al*., 2008) associated with the effects of mud loading, ground relaxation due to mud outflow, etc. Note that ground deformation (e.g. subsidence) around the inside of the caldera was not observable after 1 year post-eruption, which is likely due to the catastrophic nature of the collapse processes during caldera formation, plus the expansion of mud coverage along with its loading effect has made observing or even extrapolation of ground deformations nearly impossible.

For 1 year after the LUSI eruption, the magnitudes of subsidence inside the caldera vary between -1 and -8 meters. Meanwhile, values between -1 and -7 decimeters were recorded around caldera rim. Outside the caldera we observed only several centimeters of subsidence. After 4 years since eruption, -0.3 to -1.2 meters of subsidence is recorded around the caldera rim, while several decimeters are recorded outside the caldera. For the LUSI case, the inside of the caldera is assumed to be 0 to 1 kilometers, the rim of the caldera is assumed to be 1 to 2 kilometers, while the outside of the caldera is greater than 2 kilometers from the LUSI eruption, respectively. Figure 6a shows contours of the magnitude of subsidence for 2 years after the LUSI eruption, and Figure 6b describes the same 4 years after the eruption. In both figures, the typical cone-shaped caldera of subsidence created by the LUSI mud volcano is clearly seen. Figure 7 shows profiles of the subsidence for 1, 2, and 4 years after the LUSI eruption. It can be seen that subsidence affected mostly an area within 1 kilometer of the eruption center (i.e. inside the caldera).

For horizontal components (Table 2, figure 8 and 9) we can see displacement vectors consistently pointing toward the center of the LUSI eruption. This orientation of vectors is consistent with the type of cone-shaped pattern of subsidence that would be expected when subsurface material is extruded to the surface (e.g. a mud volcano eruption). It is difficult to explain this pattern with fault motion, since fault motion should involved discontinuity of either horizontal (strike-slip faulting) or vertical (thrust or normal faulting) motion along the trace of the fault. Thus, a combined analysis of both horizontal and vertical signatures of deformation such as we present here is crucial for investigating earthquake cycle investigation.

Table 1. Magnitude of subsidence 1, 2, and 4 years after the LUSI eruption

Spatial constrain	Point	Distance from LUSI eruption (in kilometer)	Magnitude of subsidence (in meter)		
			first 1 year from eruption	2 year since eruption	4 year since eruption
Inner caldera (0-1 km from LUSI eruption)	RIG1	0.10	-8.716	No observations	
	JBSR	0.37	-6.868		
	PBRK	0.54	-4.06		
	TOLL	0.47	-3.638		
	SIRN	0.46	-3.544		
	JTRJ	0.95	-1.732		
	PSKO	0.76	-1.564		
Rim of caldera (1-2 km from LUSI eruption)	JLSR	1.00	-0.696	-0.973	-1.250
	RMKN	1.08	-0.576	-0.783	-0.949
	SNGN	1.24	-0.542	-0.788	-0.989
	PRTL	1.32	-0.723	-0.963	-1.153
	GLAG	1.40	-0.341	-0.520	-0.679
	BPN1	1.62	-0.322	-0.454	-0.583
	1210	1.74	-0.060	-0.090	-0.130
	PJKN	1.78	-0.126	-0.156	-0.196

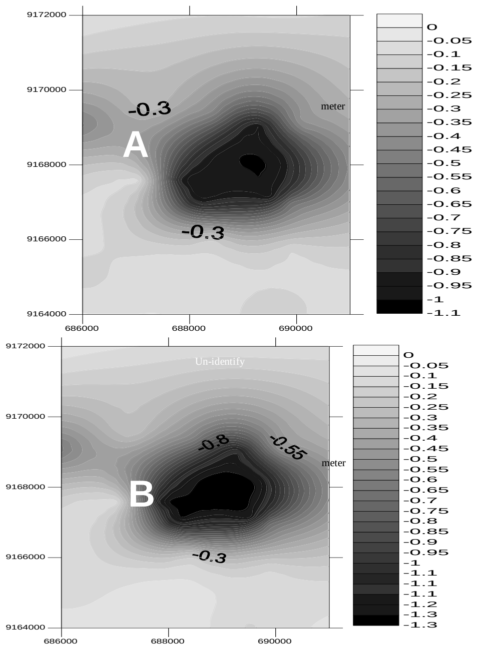

Figure 6. Filled contour graph of subsidence magnitude for 2 years after LUSI eruption (A) and 4 years after (B). The typical cone-shaped subsidence caldera is clearly seen.

	GMPL	1.84	-0.310	-0.400	-0.490
	SWH1	1.91	-0.171	-0.241	-0.301
Outer of Caldera (>2 km from LUSI eruption)	JBPR	2.32	-0.090	-0.120	-0.170
	PGN1	2.32	-0.090	-0.099	-0.159
	BMT2	2.33	-0.125	-0.211	-0.243
	BT16	2.48	-0.060	-0.100	-0.137
	BMT4	2.53	-0.069	-0.114	-0.149
	KCMT	3.21	-0.050	-0.078	-0.105
	CNDI	3.21	-0.250	-0.391	-0.565
	KLDN	3.40	-0.149	-0.190	-0.222
	GPOL	3.88	-0.105	-0.145	-0.163
	BM08	3.99	-0.080	-0.125	-0.143
	ORFF	4.41	-0.075	-0.083	-0.110

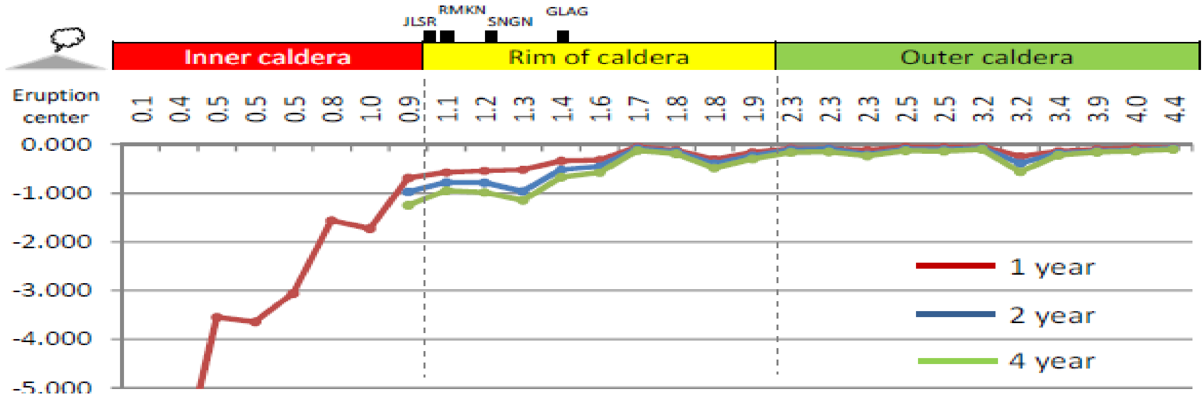

Figure 7. Subsidence profiles 1, 2, and 4 years after the LUSI eruption; X axis is distance from the eruption center (km), Y axis is magnitude of subsidence (m). Each year is representing by different color. Positions of some of the principle GPS monitoring stations (e.g. JLSR, RMKN, SNGN, GLAG) are also plotted).

Table 2. Horizontal displacements measured at GPS monitoring stations

Point name	Vector of horizontal ground displacement of random epoch	
	East (m)	*North* (m)
RIG1	-4.66	-8.716
JBSR	-2.29	-6.868
SIRN	-1.85	-3.544
TOLL	-1.92	-3.638
PBRK	-2.15	-4.060
PSKO	-0.84	-1.564
PS02	-0.52	-1.564
BND2	-0.89	-1.995
JTRJ	-0.92	-1.732
JBSR	-0.29	-0.696
RMKN	-0.20	-0.576
SNGN	-0.27	-0.542
PRTL	-0.34	-0.723
GLAG	-0.17	-0.341
BPN184	-0.11	-0.322
1210	0.00	-0.060
PJKN	-0.05	-0.126
GMPL	-0.15	-0.310
SWH1	-0.09	-0.171
JBPR	-0.02	-0.090
PGN1	-0.03	-0.090
BMT2	-0.03	-0.125

Figure 8. Horizontal ground displacement vectors around LUSI overlaid on Google Earth graphic.

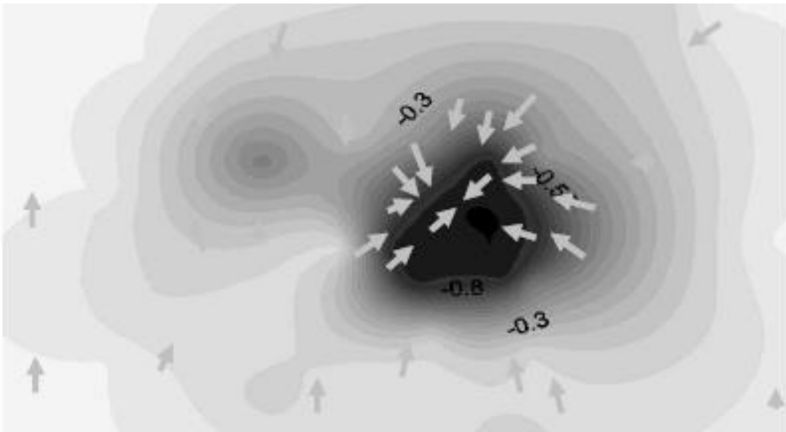

Figure 9. Horizontal ground displacement pattern around LUSI overlaid with subsidence plotted as filled contours.

4. JOGJAKARTA EARTHQUAKE VERSUS LUSI MUD VOLCANO ERUPTION (EARTHQUAKE CYCLE LESSON)

This paper is mainly focusing on learning a disaster from earthquake cycle deformation study. We will see some documentation of co-seismic event, and probably interseismic and post-seismic event. As mentioned earlier the case study will involved Jogjakarta earthquake 6.3 Mw on May 27, 2006 and LUSI mud volcano eruption on May 29, 2006 (two day a coincidence after Jogjakarta earthquake 250 km away western side) which is by some argument also relating to the earthquake activities. Bellow we will see the analysis on what has happened in Jogjakarta and LUSI and concluded how they relevant to disaster evaluation and mitigation.

Previously published studies of the LUSI mud volcano eruption hypothesis, many explain that the eruption was triggered by reactivation of a local fault (Watukosek fault) due to seismic waves from the Jogjakarta (Opak fault) earthquake. Mazzini *et al* (2007, 2009) concluded that the Jogjakarta earthquake triggered the LUSI eruption due to earthquake-induced hydrological effects that reactivated a fault in the LUSI area. Lupi *et al* (2013) use seismic reflection data that image the underground structure at the site of the LUSI eruption to identify a downward-concave layer of shale that seals the mud reservoir below. The authors use a numerical model to simulate the interaction between the shale layer and incident seismic waves generated by the Jogjakarta earthquake. According to the simulations, stresses induced by the earthquake could have been about 100 kPa, five times higher than the original estimate of 21 kPa. As a conclusion, concave rock layer capping the mud reservoir could have focused and amplified incoming seismic waves from the Jogjakarta earthquake, and could have thus reactivated the fault and triggered the LUSI mud eruption. Illustration of Jogjakarta Opak fault earthquake, Watukosek fault and LUSI eruption, etc. is given in figure 10.

Nevertheless, the ground deformation signature around the Watukosek fault and surrounding the LUSI eruption is picturing a cone-shaped subsidence and horizontal pattern toward the eruption vent that would be expected if subsurface material were extruded to the surface (e.g., in a mud volcano eruption) (fig 6, 8, 9, 10). It is hard to figure out the deformation pattern observed can be associated with fault reactivation. It is difficult to explain this pattern with fault motion, since fault motion should involved discontinuity of either horizontal (strike-slip faulting) or vertical (thrust or normal faulting) motion along the trace of the fault. On more although it is difficult to rule out the seismic focusing argument of Lupi *et al* (2013) base on our data alone, the connection of the LUSI mud volcano with the Jogjakarta earthquake seems tenuous at best.

Favored to the conclusion, Davies *et al* (2007) compare the distance and magnitude of the earthquake with the relationship between the distance and magnitude of historical earthquakes that have caused sediment liquefaction, or triggered the eruption of mud volcanoes or caused other hydrological responses, and found that by this comparison, an earthquake trigger is not expected. There were bigger, closer earthquakes that did not trigger an eruption. For all attenuation relationships being considered, tens of previous earthquakes (and for some relationships, hundreds) had significantly larger expected ground motions at LUSI than the Jogjakarta earthquake. Also, no evidence to support the concept that repeated shaking acted to shift the subsurface to a near-critical state, prior to the Jogjakarta earthquake. The change in pore pressure due to changes in static stress caused by the earthquake is ~10 Pa, which is negligible, and the amplitude of the dynamic stress induced by the Jogjakarta earthquake is 21 +33/-12 kPa, which is negligible.

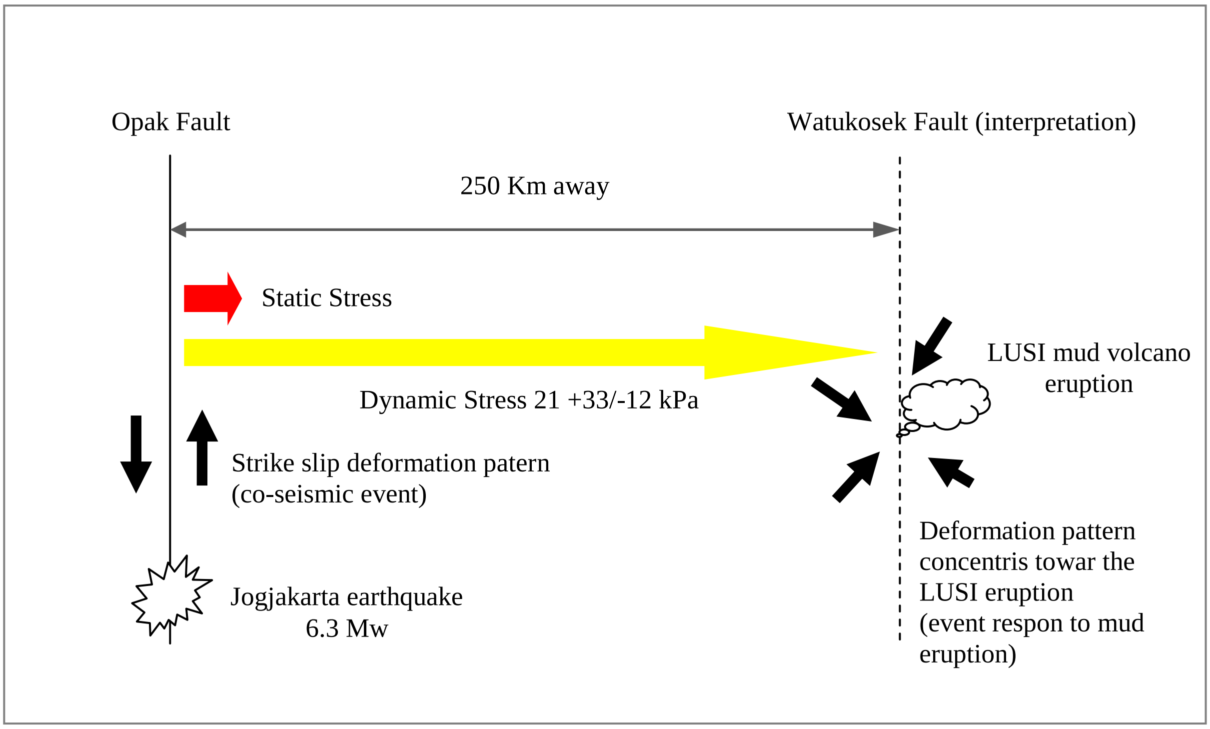

Figure 10 Illustration of Jogjakarta Opak fault earthquake, co-seismic signature, static-dynamic stress, Watukosek fault and LUSI eruption, vector horizontal displacement surrounding LUSI

5. CLOSING REMARKS

Facts show that co-seismic strike slip has occurred in Opak Fault Jogjakarta, meanwhile no sign of co-seismic strike slip or dextral has occurred in Watukosek fault instead of caldera formation due to LUSI mud volcano eruption. Lesson learn from this earthquake cycle phenomenon in the investigation area, blaming Jogjakarta earthquake to reactivation of Watukosek fault and initiate LUSI eruption is week analysis and conclusions.

References

Abidin, H.Z. , R.J Davies, M.A Kusuma, H. Andreas (2008), Subsidence and Uplift of Sidoarjo (East Java) due to the Eruption of the LUSI Mud Volcano (2006-Present) Environ Geol DOI 10.1007/s00254-008-1363-4

AndreasH., H.Z.Abidin, M.A Kusuma, P. Sumintadireja, I. Gumilar. (2010), Ground Displacement around LUSI Mud Volcano Indonesia as Inffered from GPS Surveys; *FIG Congress 2010(Facing the Challenge-Building Capacity),* , Sydney Australia, 11-16 April 2010.

Beutler, G., H. Bock, E. Brockmann, R. Dach, P. Fridez, W. Gurtner, U. Hugentobler, D.Ineichen, J. Johnson, M. Meindl, L. Mervant, M. Rothacher, S. Schaer, T. Springer, R.Weber (2001). *Bernese GPS software version 4.2.* , University of Berne, 515 pp

Hudnut KW, Bock Y, Cline M, Fang P, Feng Y, et al. 1994. Co-seismic displacements of the 1992 Landers earthquake sequence. *Bull. Seismol. Soc. Am.* 84:625–45

Davies, R.J., R.E. Swarbrick, R.J. Evans, M. Huuse (2007). "Birth of a mud volcano: East Java, 29 May 2006", *GSA Today*, Vol. 17, No. 2, February, DOI: 10.1130/GSAT01702A.1, pp. 4-9.

Davies.R.J, Michael Manga, Mark Tingay, Susila Lusianga, Richard Swarbrick (2010). "Sawolo et.al (2009) The LUSI Mud Volcano Controversy : Was it caused by Drilling" ,Marine and Petroleum Geology 27 (2010) 1651–1657

Fukushima, Y, Jim Mori, M.Hashimoto, Yasuyuki Kano (2009). Subsidence associated with the LUSI Mud eruption, East Java, investigated by SAR interferometry *Marine and Petroleum Geology xxx (2009) 1-11.*

Mazzini,A., H. Svensen, G.G. Akhmanov, B. Istadi, S. Planke (2007) Pulsating and quasi-hydrothermal mud volcanism at LUSI, Indonesia; Geophysical Research Abstracts, Vol. 9, 09677, 2007 SRef-ID: 1607-7962/gra/EGU2007-A-09677 © European Geosciences Union 2007

Mazzini, A, A. Nermoen, M. Krotkiewski, Y. Podladchikov, S. Planke, H. Svensen (2009). "Strike Slip Faulting as a Trigger Mechanism for Overpressure Release Through Piercement Structure. Implication for the LUSI Mud Volcano, Indonesia" , Marine and petroleum Geology 26 (2009) 1751–1765

M. Lupi, E.H. Saenger, F. Fchs, S.A. Miller (2013). "Lusi mud eruption trigger by geometric focusing of seismic waves" , Nature geosciences letters. Published online 21 July 2013. DOI:10.1038/NGEO1884

BIOGRAPHICAL NOTES

Heri Andreas

Academic experience: Undergraduate. (Geodesy) Institute of Technology Bandung, Graduate. (Geophysic) Institute of Technology Bandung, PhD. Student (Geodesy) Institute of Technology Bandung

Current position: Lecturer, Geodesy and Geomatic, Faculty of Earth Science and Technology, Institute of Technology Bandung

Practical experience: GPS surveying and mapping, geodynamic-deformation and control surveys, boarder demarcation, Oil support engineering, site engineering

CONTACTS

Heri Andreas
Geodesy Research Division, Institute of Technology Bandung
LABTEX IXC Jl. Ganesha 10 Bandung 40132 – Indonesia
Telp /FAX : +62 22 253 4286 / +62 22 253 4286
Email: **heri@gd.itb.ac.id**