Ground Displacements around LUSI Mud Volcano Indonesia as Inferred from GPS Surveys

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Key words : Mud Volcano, Ground Displacement, GPS, Caldera Formation

SUMMARY

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 massively and flooded the surrounding areas. The mud flow currently covers an area of about 7 square-km, covering several villages. About 40,000 people have been displaced and the mud volcano is still active after more than 3 years. The mud volcano seems to be unstoppable, and all the attempts to halt the mud eruptions have so far failed.

The eruption of the LUSI mud volcano has triggered vertical and horizontal ground displacements. In the early development of mud volcano, GPS surveys results show that subsidence is occurring at rates of 0.1 and 4 cm/day resulting in the development of an avoid-shaped sag. It is proposed that the subsidence occurs due to: (1) mud loading, (2) collapse of the overburden due to the removal of mud from the subsurface and (3) land settlement caused by surface works (e.g. construction of dykes). The recent GPS surveys indicate that the ground displacements in and around LUSI mud volcano is still continuing although it is not as big as in the early stage of development of mud volcano.

In the areas closest to the mud eruption, the previous and recent results from GPS surveys results indicated the existence of horizontal concentric vector displacements and circular depressions of vertical vector displacements around the mud volcano which is expressing caldera formation processes. This paper will mainly discuss the characteristics of early ground displacement up to recent ones around LUSI mud volcano as inferred by GPS surveys and the GPS expressing caldera formation processes.

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1. 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 (see Figure 1b,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 1 (a) LUSI mud volcano eruption, (b) crack on the floor, (c) cracks on the ground around relief well 1, (d) crack on the house in Sengon Village.

1.2 Ground Displacement at LUSI Mud Volcano

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. (see figure 1b, 1c, 1d). On 24 November a gas pipeline exploded near the mud extrusion centre, killing several people. These ground displacement furher may explain the caldera formation processes is happening on LUSI Mud Volcano. GPS observations as will explain latter in the next chapter clearly showed ground displacements that has been going on.

2. GPS OBSERVATION AND PROCESSING

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. Thirtheen GPS campaigns have been conducted between June 2006 and May 2009. Bellow (figure 2) we can see some documentation of GPS survey in the field.

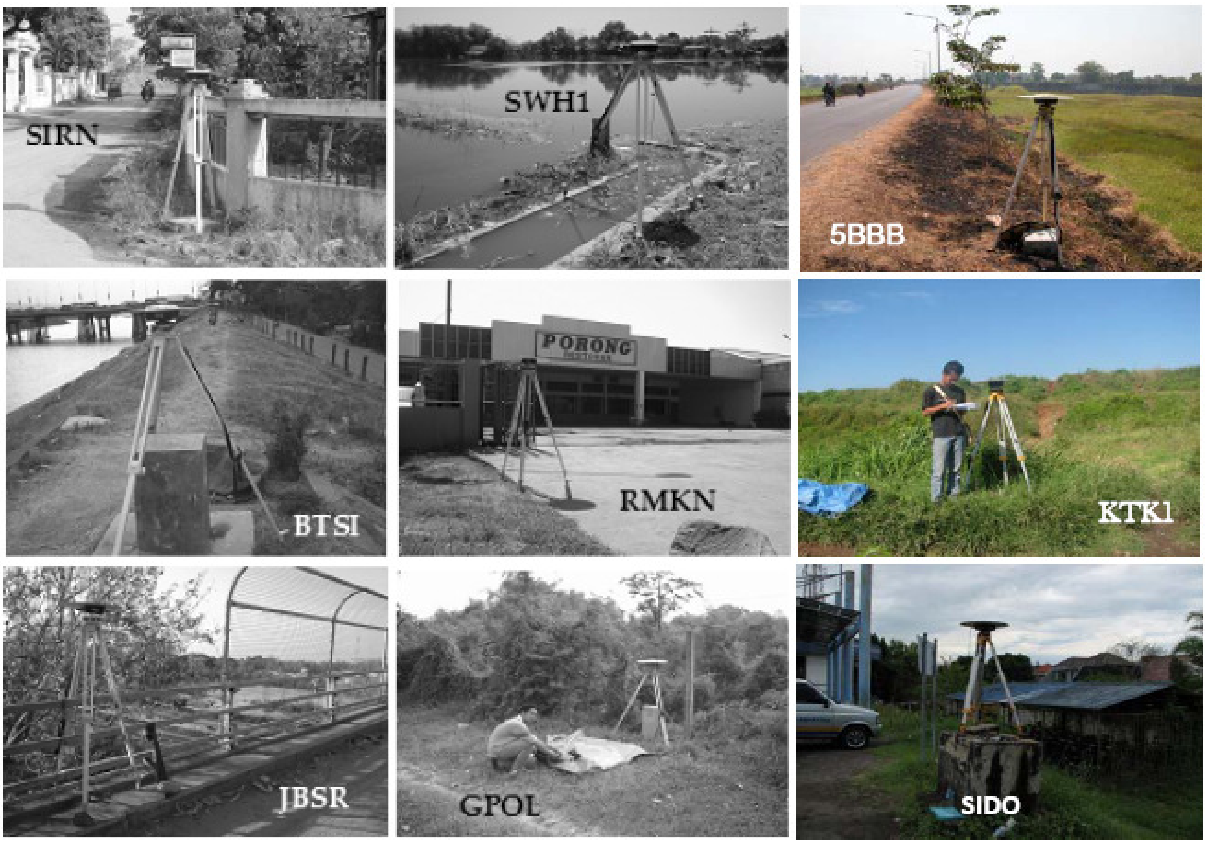

Figure 2 Some documentation of GPS survey in the field using dual-frequency geodetic-type receivers, with observation session lengths of about 5-10 hours.

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.

3. RESULT OF GROUND DISPLACEMENTS

The GPS derived displacements from the first three GPS campaigns conducted in June, July and August showed that the surface displacements in the mud volcano area of Sidoarjo have both horizontal and vertical components. In these first three months of mud extrusion it can be seen that the rates of displacements are increasing with time. In this period, the rates of horizontal and vertical displacements were up to 2 cm/day and 4 cm/day, respectively; and vertical displacements are dominated by subsidence. Based on GPS results, the affected area of displacements up to end of August 2006 is contained to about 1 km around the extrusion centre. Starting from the third campaign, more GPS stations were observed (Abidin, 2008).

GPS continuous that was set up in RW02 and RW01 between September 2006 and early 2007 give daily rate of vertical displacement or subsidence reached about 3.8 cm/day and 1.8 cm/day. The results also show that about 7-8 months after the first mud extrusion, the subsidence around the main vent area exhibits a linear trend. The horizontal displacements of those two continuous stations are about 1.0 cm/day and 0.6 cm/day (Abidin, 2008).

What happen after two and three years turn out that the ground displacement has slowering at rates. Its not 2-4 cm/day anymore but only several centimeter up to desimeter in a years time. A linier trend were replaced by exponential decay instead. The clear analysis showed that ground displacement devide into two stage which is rapid ground displacement (further will be associate with Caldera formation processes) and normal ground displacement representing adjustment from the effects of mud loading, ground relaxation due to mud outflow, etc.

From the complete result of the whole GPS surveys, unfortunately we were not getting the complete time series of ground displacement in every points of observations for the whole those more than three years time spand of observation because of the change in mud coverage area that given the consequences the number of observed GPS stations were becoming different from survey to survey, and the observed stations could not always be the same. But, fortunately we still can made a model of the ground displacement based on interpolation and extrapolation. Figure 3 show modeled of ground displacement one years and three years time after the birth of LUSI mud volcano. As asumption, only the source of mud volcano derived ground displacement (neglect the other source like ground water or gas withdrawal), and we separate between the rapid ground displacements and normal displacements.

Since the rapid ground displacement in the early stage of the birth of this LUSI mud volcano (or define also as early stage of Caldera formation processes) were exluded intentionally when we derive normal ground deformation information model, so the total of ground displacement seem smaller (e.g maximum subsidence after 1 year eruption were 1.96m and after 3 year were 3.8m). These info of normal ground deformation will be a useful information for infrastructure development planning, hazard evaluation, etc.

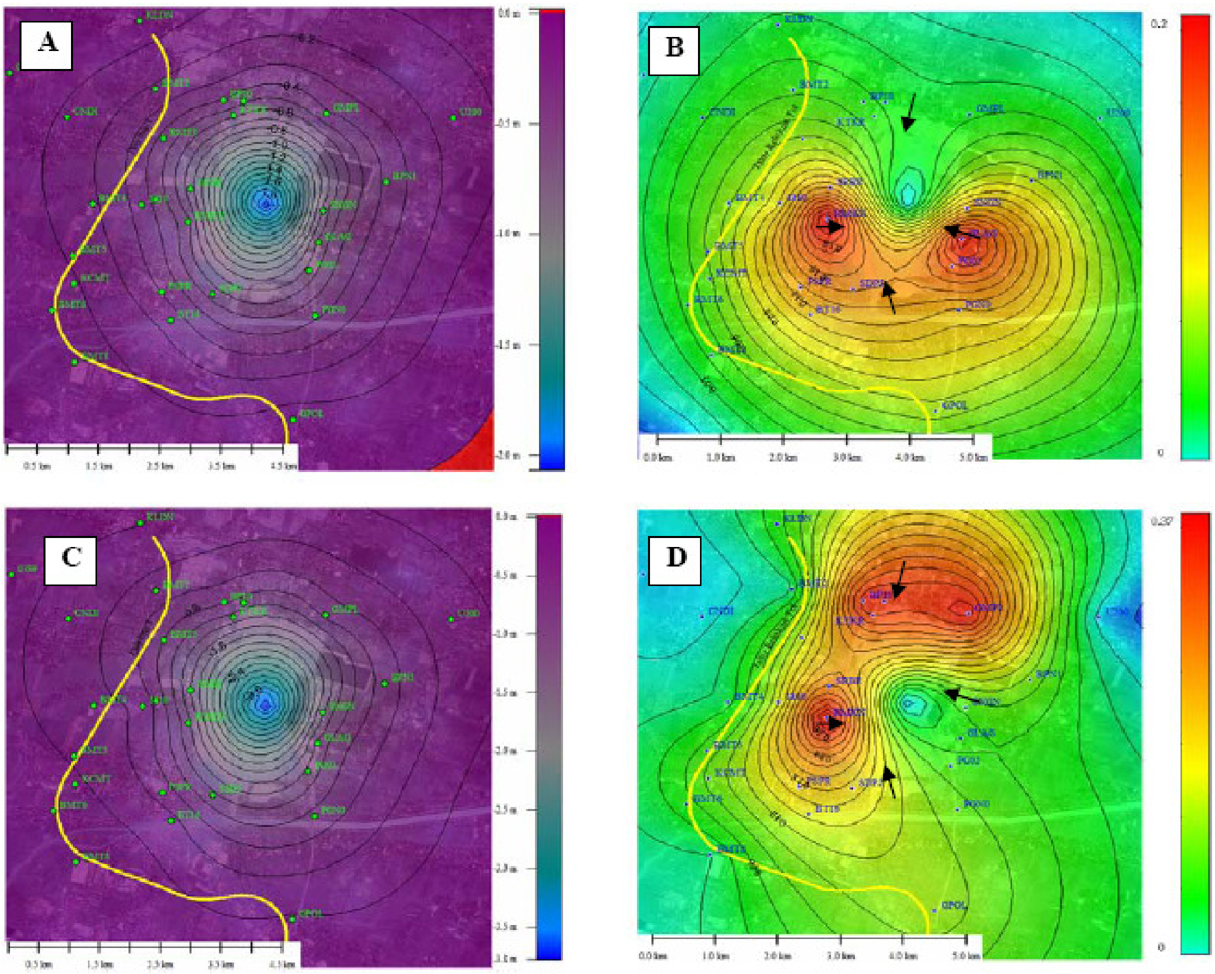

Figure 3. (a) Model derived vertical displacements after 1 year of LUSI mud volcano erruption, (b) Model derived horisontal displacements after 1 year LUSI mud volcano erruption, (c) Model derived vertical displacements after 3 year LUSI mud volcano erruption, (d) Model derived horisontal displacements after 3 year LUSI mud volcano erruption,

A very much interesting to see, the pattern of horizontal displacement given by GPS observation result (figure 3b,3c) showed concentrate outlook toward the center of subsidence. Meanwhile the vertical displacement given the model of cone subsidence (figure 3a,3c). This two information will shown good fact on explaining caldera formation processes that happening in LUSI mud volcano. Together with other informations such as field surface representation of displacement, occurred buble plotting, microseismic, etc. we can be sure that no doubt caldera formation is being develop in LUSI mud volcano.

4. CALDERA FORMATION PROCESSES

Caldera formation processes is one of main processes of the birth and development of mud volcano. Caldera formation perform as a result of adaptation of subsurface extruded material (e.g mud, water, gas) to the surface following by surface collaps which is the next result performed typical morphology of caldera. Some research clearly show the relationship between loss of volume in the shallow subsurface and caldera collapse (e.g. Acocella 2006; Aizawa *et al*. 2006; Geyer *et al*. 2006). This caldera formation mechanism in closely look seem controlled by subsidence processes. Therefore, numerous published models given the name of caldera formation processes as caldera subsidence.

As mention previously the GPS derived information together with field surface representation of displacement (cracks), and also occurred bubble plotting, micro seismic, etc were showing the good fact on explaining caldera formation processes that happening in LUSI mud volcano. We can be sure that caldera formation is being developed in LUSI mud volcano (figure 4c).

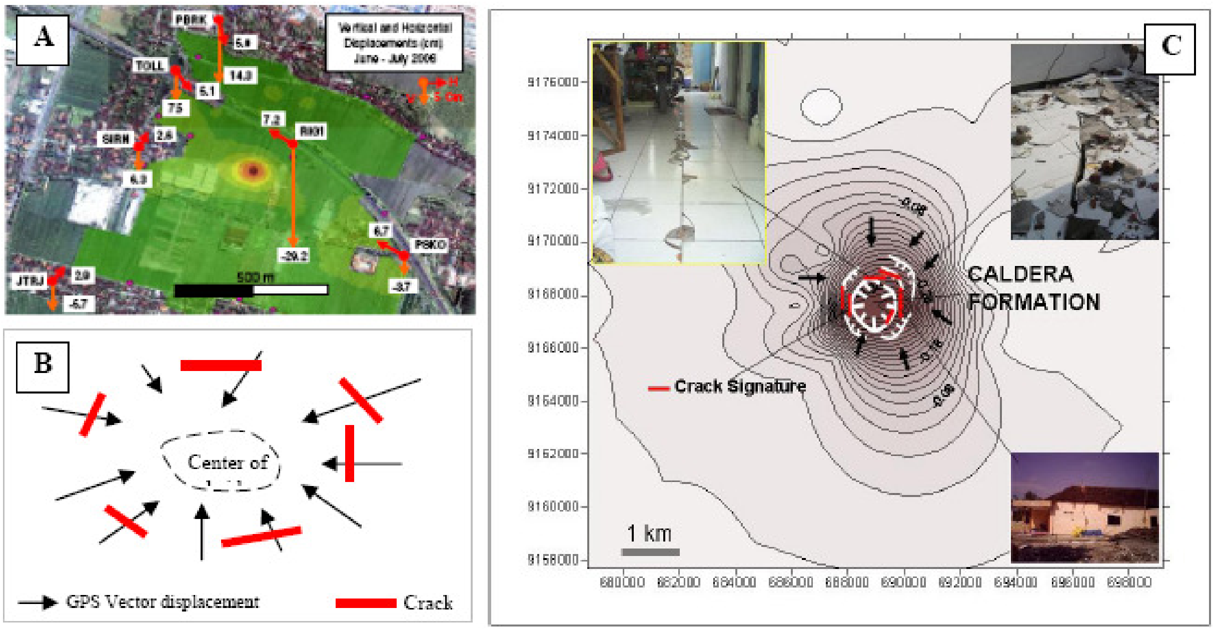

Figure. 4 (a) GPS derived displacements, June to July2006; (b) Data overlay illustration of crack signatures and horizontal displacement from GPS result, (c) Illustration of caldera formation processes on recently birth LUSI Mud Volcano

Caldera formation processes around LUSI mud volcano has given a consequences strongly to people and their environment. Many houses were cracking (even wider by the times), some bridge suffering cracked and some of them even had to dismantle, street also suffering cracked, etc. On 27 September 2006, the ground displacements had also caused a dextral (right lateral) movement of a railroad located on the western side of the mud extrusion. On 22 November 2006 Gas Pipeline were exploded and killed 18 people. Some gas and bubble is now occurring in some village as well, meanwhile micro earthquake was happening around caldera formation faulting, etc.

By seeing those above fact, this caldera formation processes indeed turn out to be a new problem to people and their environment besides mud flooding caused by LUSI mud volcano. Some people were killed indeed, not less money has to be spent for damaging housing, damaging infrastructure, etc. indeed. So, in this cased we surely have to figure out how to deal with this phenomenon for now and the future (e.g. evaluate the infrastructure development and evaluate the hazard mitigation program).

5. SUMMARY

Considering the effects of mud loading, ground relaxation due to mud outflow, etc., ground displacements occurred. 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. GPS results show that the surface displacements in the mud volcano area of Sidoarjo have both horizontal and vertical components. In the first three months of mud extrusion it can be seen that the rates of displacements are increasing with time. In this period, the rates of horizontal and vertical displacements were up to 2 cm/day and 4 cm/day, respectively; and vertical displacements are dominated by subsidence. GPS continuous that was set up in RW02 and RW01 between September 2006 and early 2007 give daily rate of vertical displacement or subsidence reached about 3.8 cm/day and 1.8 cm/day. The horizontal displacements of those two continuous stations are about 1.0 cm/day and 0.6 cm/day.

Based on GPS results, the affected area of displacements up to early 2007 is contained to about 1-2 km around the extrusion centre. The results also show that the subsidence around the main vent area exhibits a linear trend. But, what happen after two and three years turn out that the ground displacement has slowering at rate. Its not 2-4 cm/day anymore but only several centimeter up to desimeter in a years time. A linier trend were replaced by exponential decay instead. The clear analysis showed that ground displacement devide into two stage which is rapid ground displacement (that already explained to be associate with Caldera formation processes) and normal ground displacement representing adjustment from the effects of mud loading, ground relaxation due to mud outflow, etc. These info of normal ground deformation as well as Caldera Formation Processes will be a useful information for infrastructure development planning, hazard evaluation, etc.

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BIOGRAPHICAL NOTES

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