DIFFERENTIAL INSAR MONITORING OF THE LAMPUR SIDOARJO MUD VOLCANO
(JAVA, INDONESIA) USING ALOS PALSAR IMAGERY

Adam Thomas(1), Rachel Holley(1), Richard Burren(1), Chris Meikle(2), David Shilston(2)

(1) Fugro NPA Limited, Crockham Park, Edenbridge, Kent TN8 6SR, United Kingdom
Email: a.thomas@fugro-npa.com, r.holley@fugro-npa.com, r.burren@fugro-npa.com

(2) Atkins Limited, Woodcote Grove, Ashley Road, Epsom, Surrey, KT18 5BW, United Kingdom
Email: chris.meikle@atkinsglobal.com, david.shilston@atkinsglobal.com

ABSTRACT

The LUSI mud volcano (Java, Indonesia), colloquially called LUSI, first appeared in May 2006. Its cause, whether the result of natural or anthropogenic activities (or a combination of both), is still being debated within the academic, engineering and political communities.

The mud volcano expels up to 150,000 m³ of mud per day; and over time, this large volume of mud has had a major environmental and economic impact on the region. The mud flow from LUSI has now covered ~6 km² to depths some tens of metres, displacing approximately 30,000 residents; and continues to threaten local communities, businesses and industry. With such a large volume of mud being expelled each day it is inevitable (as with onshore oil and gas production fields) that there will be some ground surface movement and instability issues at the mud source (the main vent), and in the vicinity of the mud volcano footprint.

Due to the dynamic ground surface conditions, engineers and academics alike have found it difficult to reliably monitor ground surface movements within the effected region using conventional surveying techniques. Consequently, engineers responsible for the risk assessment of ground surface instabilities within the proximity of LUSI have called upon the use of satellite interferometry to continually monitor the hazard.

The Advanced Land Observing Satellite (ALOS), launched on 24th January 2006, carries onboard an L-band Synthetic Aperture Radar (SAR) instrument called PALSAR (Phased Array type L-band Synthetic Aperture Radar). In contrast to established C-band (5.6cm wavelength) SAR instruments onboard ERS-1 & -2, Envisat, Radarsat-1, and the recently launched Radarsat-2 satellite, PALSAR’s (L-band/23.8cm wavelength) instrument presents a number of advantages, including the ability to map larger-scale ground motions, over relatively short timeframes, in tropical environments, without suffering as significantly from signal decorrelation associated with C-band imagery.

This paper presents the results of a 2-year ALOS PALSAR Differential Interferometric (DifSAR) monitoring campaign across the LUSI mud volcano. DifSAR processing was applied to a sequence of images acquired on a 3 to 6-month basis between May 2006 and May 2008. The results highlight the capability of ALOS PALSAR in detecting decimetres of coherent ground subsidence to assist engineers in their analysis of the structure, dynamics and overall stability of the mud volcano and the surrounding region.

1. INTRODUCTION

The colloquially named ‘LUSI’ mud volcano (Lumpur - Sidoarjo) began erupting on the 29th May 2006, during the drilling of an exploratory gas well in the Porong District of Java, Indonesia.

Over the past three years, the continuous flow of hot toxic mud from LUSI has reached rates of between 100,000 and 160,000 cubic metres per day and has inundated an area of about 6.4 square kilometres despite attempts by the local authorities to retain the flow with the construction of large earth dams.

Figure 1. The construction of large earth dams to retain...

Thirteen people have lost their lives and more than 30,000 people have been displaced from their homes by LUSI’s eruption. The mud flow has inundated houses, factories, farmland and the Surabaya-Gempol Toll Road. It has placed at risk a railway line, the surface water drainage and irrigation network, ecosystems, water and gas pipelines, and fibre-optic cables connecting Surabaya to Eastern Indonesia.

Figure 2. The impact of mud inundation. Note the depth of mud in relation to the building roof adjacent to the earth dam. Photograph taken 29th May 2007. © Atkins Ltd. 2007.

The ongoing physical, economic and political effects of LUSI’s eruption have been widely documented in newspapers, on the internet and in academic journals. However the origin of the LUSI mud volcano is the subject of considerable controversy, with two competing hypotheses. The first proposes that the eruption was the result of an underground blowout caused by the drilling of the Banjarpanji-1 gas exploration well into very deep over-pressured strata [1]. The second suggests it was triggered by an earthquake two days earlier, 300 kilometres east of Porong, and this re-activated the local Watukosek Fault System which acted as conduit from the over-pressurised strata [2]. Within the scientific and academic communities, the well blowout hypothesis is widely supported as being the most likely.

In the period shortly after LUSI’s initial eruption, there was much political sensitivity regarding its cause, and considerable concern within the local community. People wanted to know what impact the erupting mud was going to have, how long it would last and what mitigating measures would be implemented.

2. HAZARD MONITORING

In May 2007 Atkins made an initial site visit to reconnoitre the mud volcano and its surrounding area to make an initial assessment of the risks and hazards associated with the mud volcano. LUSI had been erupting for about one year at the time of the visit and best estimates of the longevity were that it would continue to erupt for about 10 to 40 years. Judgements about LUSI’s behaviour and the risk posed local property, industry and businesses in the months and years to come were necessarily tentative. It was suggested that a limited programme of hazard monitoring using remote sensing would best meet the requirements for regularly updating the initial risk assessment.

Remote sensing specialists Fugro NPA helped design and implement a hazard monitoring programme that made use of two types of satellite mapping: VHR (Very High Resolution) optical imagery and satellite InSAR (Interferometric Synthetic Aperture Radar). The imagery was procured and processed by Fugro NPA’s InSAR Surveying team and analysed by Atkins.

Figure 3. Sequence of IKONOS satellite images acquired across the location of the mud volcano (center of image). Images were acquired on the 14th November 2002 (left), 31st October 2006 (middle) and 5th January 2007 (right). Images © GeoEye and Fugro NPA Ltd.
3. VERY HIGH RESOLUTION IMAGERY

The physical consequences of LUSI have been observed and recorded using regularly acquired VHR optical images from the IKONOS and Quickbird satellites. Comparisons made between images taken every 1 to 3 months have enabled good assessments to be made. During analysis of the VHR optical imagery, attention was paid to the distribution of mudflows from the vent, the construction and performance of the earth dams, changes in behaviour of the nearby rivers, changes in land use, distribution of surface water flooding, and lateral migration of the mud volcano vent. All observed data were recorded within a GIS (Geographical Information System) geo-database (Fig. 4).

4. ALOS PALSAR INTERFEROMETRY

In addition to the surface changes due to mud inundation, ground subsidence due to withdrawal of material from subsurface levels was a key concern. In addition to the effects of such subsidence on the local environment and infrastructure, the location and magnitude of the subsidence signals also gives valuable information about the subsurface structure and dynamics of the volcano, essential to understanding the ongoing risks. Satellite-based InSAR techniques provide measurements of ground deformation, meeting the requirement for a remote monitoring solution.

The combination of largely agricultural land use and the large amount of ground movement observed and predicted across the area of interest would result in poor interferometric coherence in conventional C-band (5.6 cm wavelength) interferograms. The longer 23.6 cm wavelength of L-band SAR data increases coherence in vegetated areas, and enables measurement of larger magnitude deformation signals.

Figure 4. An extract from the GIS geodatabase (05/12/2008) used to record the physical changes associated with the LUSI mud volcano. Image © Atkins Ltd. 2009.
ALOS PALSAR is an L-band instrument operated by JAXA (Japanese Aerospace Exploration Agency). Fugro NPA acquired a sequence of ALOS PALSAR images at approximately 6-month intervals (Tab. 1), starting from 19th May 2006 (pre-eruption). Fig. 5 shows three unwrapped interferograms; in each case the mud volcano can be seen as an approximately rectangular area of incoherence surrounded by between 17cm and 108cm of line-of-sight subsidence. By comparison with Fig. 3 and Fig. 4, the rectangular patch of incoherence can be seen to correspond to the area inundated by mudflows from the volcano.

5. MODELLING

These interferograms enabled construction of three-dimensional models of the ground surface deformation associated with LUSI. This revealed a primary area of subsidence surrounding the mudflow extent; this is most severe near the vent, where it is difficult to monitor due to loss of coherence over the constantly-changing mudflow. To the west of the mudflow extent there is a zone of secondary subsidence, and there is a zone of lesser magnitude uplift to the north east (Fig. 6). Deformation magnitude was highest in the first interferogram period, spanning the beginning of the eruption, however noticeable deformation has occurred in each of the subsequent interferograms, indicating ongoing subsidence of the area.

Thus far, the immediate effects of LUSI (specifically the mud flow extent and ground surface deformation) have not had an impact on the client’s site.

<table>
<thead>
<tr>
<th>Image date</th>
<th>Orbit mode</th>
<th>Incidence angle</th>
<th>Spatial resolution (m)</th>
<th>Differential interferograms</th>
</tr>
</thead>
<tbody>
<tr>
<td>19th May 2006</td>
<td>Descending</td>
<td>47°</td>
<td>6</td>
<td>↑</td>
</tr>
<tr>
<td>19th November 2006</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
</tr>
<tr>
<td>19th February 2007</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
</tr>
<tr>
<td>22nd August 2007</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
</tr>
<tr>
<td>7th January 2008</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
</tr>
<tr>
<td>24th May 2008</td>
<td></td>
<td></td>
<td></td>
<td>↑</td>
</tr>
</tbody>
</table>

*Table 1. ALOS PALSAR image acquisitions, parameters and differential interferograms used during the monitoring campaign.*

Figure 5. Differential Interferograms spanning 19th May 2006 to 19th November 2006 and 19th February
6. CONCLUSIONS

Since its initiation on 29th May 2006, LUSI’s eruption has had, and continues to have, a devastating effect on the Porong District of Eastern Java; and there are no signs that the mud flow is decreasing. The flow of mud and ground surface deformation has caused significant physical, environmental, economical and social damage to the local and regional communities. The remaining lifespan of LUSI’s eruption is still not known, but best estimates are that it will continue to erupt for decades and not just a few years.

The sequence of differential interferograms produced so far are an excellent demonstration of the capabilities of the L-band ALOS PALSAR sensor. The results, derived remotely and at a comparatively low cost, have given the team and their client a unique insight into the evolution of ground surface deformation across the mud volcano, even with variable levels of coherence across the site.

For now, a continued programme of regular remote monitoring of the mud flow extent and ground surface deformation, such as the one designed and implemented by the team, will provide a valuable resource for updating geohazard and risk assessments, and allow site owners within the vicinity of LUSI to better manage their assets.

7. REFERENCES
