DEFORMATION OF BATUR VOLCANO INFERRED FROM GPS MEASUREMENTS

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ABSTRACT

Batur volcano is an active volcano located in north-eastern part of Bali Island. In the period of 1994 and 1999, the volcano erupted, resulting in three new craters. GPS surveys for monitoring the deformation of Batur volcano has been carried out in May 1999 and February 2001. Nine existing EDM benchmarks in the vicinity of the outer caldera rim and the crater of the volcano were occupied by employing five geodetic double-frequency GPS receivers. The pattern of the horizontal displacement is mostly characterized by radially directing direction toward to the volcano. It seems the volcano was experiencing a deflation process with the magnitudes of about 0.8 to 6 cm. The estimated pressure source based on Mogi model is located around the first crater with the depth of about 8 km beneath the caldera base

I. INTRODUCTION

Some understanding of magma conduits in volcanoes can be achieved from seismic, tomography, gravity, or magnetic fields analysis. The study of ground deformations (displacement, tilt, and strain) also contributes to this understanding, but it requires observations before and after eruption periods of interest. Dvorak and Dzurisin have conducted recent synthesis of volcano geodesy. One of their main conclusions is that geodesy yields estimate of magma supply rates, the location of sources, and, in some cases, the size and shape of complex magma reservoirs. [Beauducel, et. al, 1999]

In this paper, we attempt to identify the deformation of Batur volcano, an active stratovolcano located on northeastern Bali Island, by using GPS method. The historically active Batur volcano is located at the center of two concentric calderas NW of Agung volcano. The SE side of the larger 10 x 13 km caldera contains a caldera lake. The inner 7.5-km-wide caldera, which was formed during emplacement of the Bali (or Ubud) ignimbrite, has been dated at about 23,670 and 28,500 years. The SE wall of the inner caldera lies beneath Lake Batur; Batur cone has been constructed within the inner caldera to a height above the outer caldera rim. The Batur stratovolcano has produced vents over much of the inner caldera, but a NE-SW fissure system has localized the Batur I, II, and III craters along the summit ridge. Historical eruptions have been characterized by mild-to-moderate explosive activity sometimes accompanied by lava emission. Basaltic lava flows from both summit and flank vents have reached the caldera floor and the shores of Lake Batur in historical time. After reviewing the recent activity of the volcano, we present a displacement analysis of the GPS result from two epochs GPS measurement carried out in May 1999 and February 2001. A half-space Mogi model is then applied in order to estimate a location of the pressure source.

II. RECENT ACTIVITIES

Sulaeman [2001] has reported the recent activity of Batur volcano during the 1994 - 1999 period. The volcano produced at least five eruptions in August 1994, November 1997, June 1998, February 1999 and March 1999. Three new craters were formed as the

result of those successive eruptions. Most of the eruptions were alarmed by the significantly increasing of the number of the volcanic earthquake. Only the June 1998 and February 1999 eruptions were not clearly signed by the increasing of the volcanic earthquake, but the seismograph recording was mostly dominated by the volcanic tremors. The highest cumulative energy of 2.16×10^{17} erg occurred just before the November 1997 eruption. The cumulative energy of the August 1994, June 1998, February 1999 and March 1999, respectively, were about 1.34×10^{16} erg, 2.2×10^{15} erg, 1.95×10^{14} erg, and 1.91×10^{16} erg.

Volcanological Survey of Indonesia (VSI) reported that in the beginning on 4 August 1994, the daily number of A-type volcanic earthquakes increased to 14, two days later 125 events were registered. An eruption from the eastern part of the summit caused ashfall as far as 6-km west southwestward. Incandescent lava fragments and black smoke were rejected to heights of 300 m. The eruption generated 960 explosions through 11 August 1994. Volcanic tremor recorded on 13 August had maximum amplitude of 4.5 mm, but was increasing. By 14 August, when lava reached the surface, the tremor amplitude was 23 mm. The August 1994 eruption marked the first significant eruptive in 18 years.

During the week of 9-15 March 1999, white ash plumes rose 10-100 m above the crater. Booming noises were heard six times, and volcanic earthquakes increased drastically compared to the previous week (see Figure 1). It was later determined that an ash eruption had begun on 15 March, sending bluish-white plumes 10-50 m high. On 17 March, two relatively recent craters merged when a connecting ridge collapsed as a result of earthquakes and small eruptions. Volcanic activity was dominated by emission (small explosion) during the week of 23-29 March, the eruption was white-blue in color, rising 10-100 m above the crater rim. Booming noises were heard three times on 22 March, but no glow was observed. Reports were not available for most of April, but during late April through the middle of May the seismic record was dominated by explosion events (see Figure 2).

Figure 1. The monthly number of volcanic earthquakes during Jan. 1999 to April 2001.

Figure 2. The monthly number of explosion during March – July 1999

Six explosions on 17 May ejected materials that fell around the crater. Another explosion on 25 May was accomplished by incandescent ejection that fell around the crater. Explosion sounds were heard on 17 occasions during the week of 25-31 May. White ash emissions rose only to 25 m during 1-14 June, but varied between 10 and 100 m rest of the month. Similar activity continued through mid-July, and a variable rumbling noise was heard the week of 13-19 July.

Although there were no any eruptions after the 1999 eruption, seismic recording still detected the number of the volcanic earthquake until the last of 2000, but gradually decreasing. Starting from the beginning of 2001 there were no available data recorded by seismograph. The newest activity during April 2001 reported by VSI indicates there were only one deep and four shallow volcanic earthquakes recorded by seismograph. Five small explosion events were also reported. During this time, the volcano remained at Alert level 2 on a scale of 1-14.

III. GPS SURVEYS

GPS network for monitoring the deformation of Batur volcano, as shown in Figure 3, is based on the existing benchmarks of EDM survey conducted by Volcanological Survey of Indonesia (VSI). Nine EDM benchmarks in the vicinity of the outer caldera rim and crater of the volcano were occupied by employing five geodetic double-frequency GPS receivers. GPS data were recorded at every 30-second for about 10 hours of observation with 15° mask angle. GPS network is computed radially from DB01 in which its coordinates are derived from the zero-order control point at Bakosurtanal office in Cibinong, Bogor.

Figure 3. GPS Network in Batur Volcano.

The collected GPS data were processed by using GPS scientific processing software, Bernese 4.2. Basically, the main goal of the GPS processing is to reduce several biases inherent in the collected GPS data, so that the final coordinate is expected relatively free from the effects of the errors and biases. In this paper, we applied the processing strategies as briefly described below. Due to a relatively small size of the network (8 km for the longest baseline), the residual differential systematic biases caused by the ionospheric refraction and orbital errors will be relatively quite small. However, we employed the precise orbit information simultaneously with IERS Earth Orientation Parameters. The tropospheric zenith delay was reduced in two steps; the first we applied Sastamoinen as an apriori model and, the second, we estimated the zenith delay parameters by using Kalman filtering process. The results from both steps shows only the horizontal precision can be improved, while the vertical one was degraded. Accordingly, for further analysis, we present only the horizontal displacement. Furthermore, in order to minimize the noise of GPS phase data, we used narrow lane combination to determine the final coordinates of the stations.

IV. GPS RESULTS

The relative horizontal displacements with respect to DB01 are presented in local-topocentric coordinate system, shown in Table 1 and and Figure 4. From Figure 4, it is clearly seen that the pattern of the horizontal displacement is mostly characterized by radially directing toward to the volcano except for DB14, which moves outward from the volcano. The largest horizontal displacement of about 6-cm occurs at DB09, while the

smallest, 0.8-cm, is experienced by DB03. DB06 is not concluded since its the standard deviation is larger than the magnitude of the displacement.

Table 1. Relative Horizontal Displacement With Respect to DB01

GPS Site	N	δ_N	E	δ_E	Magnitude	δ_M
	in centimetres					
DB02	-2.67	0.62	-1.70	0.37	3.16	0.72
DB03	-0.56	0.32	-0.62	0.20	0.84	0.38
DB06	0.45	0.67	-0.45	0.35	0.64	0.75
DB09	-2.16	0.31	5.79	0.20	6.18	0.36
DB11	-3.05	0.24	-1.25	0.15	3.30	0.28
DB12	-2.33	0.25	0.45	0.16	2.37	0.30
DB13	2.69	0.61	1.88	0.35	3.28	0.70
DB14	-1.92	0.32	1.60	0.18	2.50	0.37

The horizontal displacements shown in Figure 4, indicating that volcano is deflating. The deflationary deformation is prominent amounting to about 3 cm/yr in the western part of the summit. This result consistent with the seismic information as described in the previous discussion, from which the volcanic activity gradually decreased after the 1999 eruption and only a few shallow volcanic earthquakes were recorded by the seismograph in the beginning of 2001.

Figure 4. Relative Horizontal Displacement With Respect to DB01.

V. PRESSURE SOURCE

The Mogi solution is an effective model at estimating the location and magnitude of the pressure source from ground deformation [Kimata, 2000]. The brief concept of Mogi model is shown in Figure 5. In this paper, we applied Nishi approach to implement Mogi model. The approach is based on the comparison between the observed baseline lengths and the computed baseline lengths from Mogi model.

In such approach, change of the baseline length (ΔL_{12}) between point-1 (x_1, y_1) and point-2 (x_2, y_2) computed by using the following formula [Abidin, 2000] :

$$\Delta L_{12} = \frac{(x_2 - x_1) \cdot X_{12} + (y_2 - y_1) \cdot Y_{12}}{R_1^3 \cdot R_2^3 \cdot L_{12}} \cdot k \quad (1)$$

In the above formula, R_i , X_{12} and Y_{12} are computed using the following relations :

$$R_i = \{(x_i - x)^2 + (y_i - y)^2 + z^2\}^{1/2}, (i = 1, 2),$$

$$k = 3a^3 \cdot p / (4\mu)$$

$$X_{12} = (x_2 - x) \cdot R_1^3 - (x_1 - x) \cdot R_2^3,$$

$$L_{12} = \text{baseline length connecting point 1 to 2}$$

$$Y_{12} = (y_2 - y) \cdot R_1^3 - (y_1 - y) \cdot R_2^3,$$

$$(x, y, z) = \text{coordinate of the pressure source}$$

The pressure source location is estimated by minimizing the following function :

$$\chi^2 = \sum_{i=1}^N \left(\frac{\Delta L_i^{\text{obs}} - \Delta L_i^{\text{calc}}}{\sigma_i} \right)^2, \quad (2)$$

where $\Delta L_{12}^{\text{obs}}$ dan $\Delta L_{12}^{\text{calc}}$ are changes of the observed and computed baseline lengths respectively, and σ_i is the standard deviation of change of the observed baseline lengths.

Figure 5. Mogi model.

Assuming that the obtained displacement is representing actual deformation, Mogi model is then applied to estimate the pressure source location. The estimated pressure source is located about 1.3 km northeast from DB11 (Crater I) with about 8 km in depth from the base of caldera, as indicated in Figure 6. The corresponding hange of the deformation volume is about $0.63 \times 10^4 \text{ m}^3$.

Figure 6. Estimated Pressure Source Location.

VI. CONCLUSION

We conducted the first GPS survey in Batur volcano in May 1999 when the volcano was very active and the second survey conducted in February 2001 when the volcanic activity was relatively low. The results from the two surveys show that GPS network detects the deflation process with the magnitude of about 0.8-6 cm in two years. In this case, the pattern of the horizontal displacements is mostly characterized by radially directing toward to the volcano craters. Based on GPS surveys results, the pressure source is estimated to be located beneath around the first crater with the depth of about 8 km from the caldera base.

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