Location and Pressures Change Prediction of Bromo Volcano Magma Chamber Using Inversion Scheme

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Abstract Bromo volcano is one of active volcanoes in Indonesia. It has erupted at least 50 times since 1775 and has been monitored by Global Positioning System (GPS) since 1989. We applied the Levenberg-Marquardt inversion scheme to estimate the physical parameters contributing to the surface deformation. Physical parameters obtained by the inversion scheme such as magma chamber location and volume change are useful in monitoring and predicting the activity of Bromo volcano. From our calculation it is revealed that the depth of the magma chamber d = 6307.6 m, radius of magma chamber α = 1098.6 m and pressure change $\Delta P \approx$ 1.0 MPa.

1. Introduction

Bromo volcano is one of active volcanoes type A in Indonesia which has erupted at least 50 times since 1775[1], for 2 decade Bromo volcano has erupted 5 times, in 1995, 2000, 2004, 2010, and 2011. Bromo volcano has been monitored by GPS and EDM since 1989. Abidin, et al.[1] has published report on surface deformation of Bromo volcano as detected by GPS and henceforth there is no more analysis and publication about Bromo volcano.

On catalog book published by PVMBG (Center for Volcanology and Geological Hazard Mitigation) we found Map of GPS distribution on 2008, which shows 8 point positions of GPS on Bromo volcano. We tried to generate deformation data based on the map using point pressure source model or Mogi model[2], then we applied the Levenberg-Marquardt (LM) scheme to predict physical parameters contributed to deformation of Bromo such as magma chamber location and the volume change[7].

2. Basic Theory

Bromo Volcano

Based on historical records, volcanic eruption of Bromo volcano has been recorded since 1804. Types of its eruption are effusive and explosive from the central crater. Over two decades, Bromo volcano has erupted five times in 1995, 2000, 2004, 2010, and 2011.Bromo volcano has been monitored using GPS and EDM since 1989.

Figure 1. Bromo volcano in 2010 (picture by Fajidi)[10]

Current Bromo activity mainly is characterized by formation of thin white smoke blowing with height of about 50 m to 100m from the crater and generally spread to the west and northwest direction. The height and intensity of the blown volcanic gas usually increase under heavy rain fall which is related to characteristics of phreatic eruption as a result of heating of surface and hydrothermal water by heat rocks or magma (Fig. 1).

3. Point Pressure source

Surface deformation of a volcano is controlled by the shape and size of the source, the increment of pressure, and the elastic properties of the medium. The deformation is proportional to the ratio of the cavity pressure change to the half-space elastic modulus $\Delta P/G$, and Poisson's ratio[2]. Mogi model assumes that the crust is half-elastic medium and surface deformation caused by pressure source in the form of a spherical of magma which is locate data certain depth. If changes in hydrostatic pressure take place on chamber, the deformation will occur symmetrically. The model input required in the model Mogi point pressure source are the depth (d), the radial distance to the source of pressure monitoring points (r), and changes in volume (ΔV).

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \alpha^3 \Delta P \frac{(1-\upsilon)}{G} \begin{pmatrix} \frac{x}{R^3} \\ \frac{y}{R^3} \\ \frac{d}{R^3} \end{pmatrix} \quad (1)$$

Where υ = poisons ratio, G = shear modulus, and ΔP = Pressure change. u, v, w are the changes of positional the point $x, y, 0$ respectively and $R = \sqrt{x^2 + y^2 + d^2}$ is the radial distance from a point to the surface. It is illustrated graphically in Fig. 2. An example of surface deformation based on Mogi model is shown in Fig. 3 and Fig. 4 in term of horizontal and vertical displacements. The input are a = 1000 m, d = 1000 m , x-min= -1000, x-max = -1000, ΔP /G = 0.001 , and υ = 0.25 respectively. The displacement vector which has radial direction to the source has a magnitude

$$U_r = \sqrt{u^2 + v^2 + w^2} = \alpha^3 \Delta P \frac{(1-\upsilon)}{G} \frac{1}{R^2} \quad (2)$$

Its magnitude varies inversely with squared distance from the center of cavity. The location of the source depth can be estimated by calculating $\left(w / U_r \right) r$ where $U_r = \sqrt{u^2 + v^2}$. Pressure changes can be estimated using the relationship between volume of surface deformation and speed of lava discharge. Relationship between of surface deformation $\left(\Delta V_{uplift}\right)$ with the change of volume on the center of pressure $\left(\Delta V_{injection}\right)$is expressed as the equation

$V_{uplift} = 2(1-v)\Delta V_{injection}$ with v is poisons' ratio. Mogi model has been used for examples by Murray et al.[4], Fialko[5], Larson[6], Materlark[8], and Srigutomo[9].

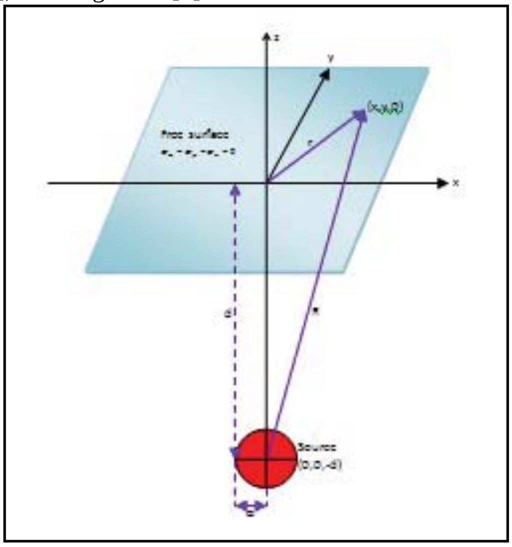
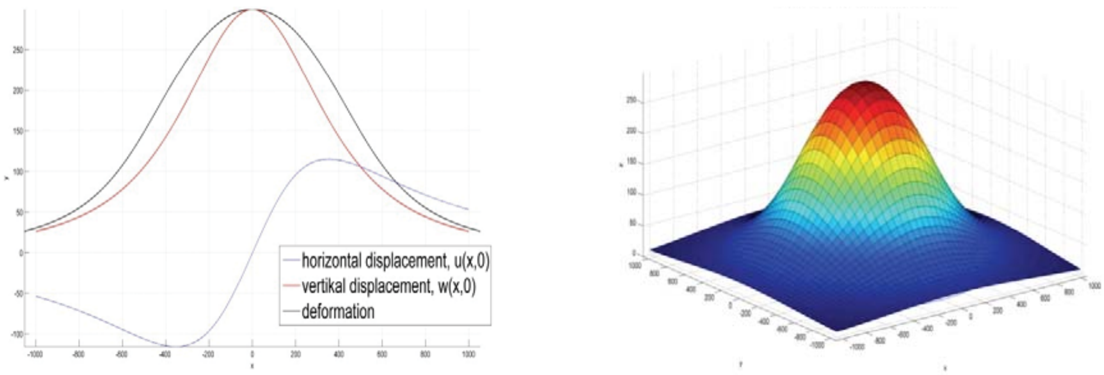
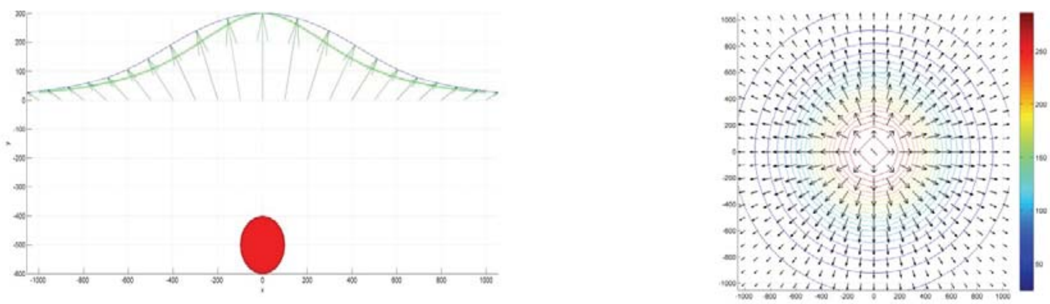


Figure2. Geometry of source in elastic half space (redrawn based on Lisowski[2])



(a) (b)

Figure3. (a) Horizontal and vertical displacements using Mogi model. (b) 3D surface displacement



(a) (b)

Figure 4. (a) Surface deformation. (b) Displacement vectors using Mogi model.

4. Inversion Scheme

Based on the observation of a system in term of data, inversion is a mathematical technique to estimate the physical parameters that characterize the system[7]. For a non-linear inversion scheme, we can use relation between the forward operator ***G***, the model parameters **m**, and the data **d** as

$$\mathbf{G}(\mathbf{m}) = \mathbf{d} \tag{3}$$

In the Mogi model, the parameters that we seek are (α, ΔP, υ) which generate calculated data that are best fitted to the observed data. By assuming the measurement errors are normally distributed, we minimize the sum of the squared error that normalized by the maximum likelihood principle, respective to their standard deviations σ,

$$F(\mathbf{m}) = \sum_{i=1}^{m} \left(\frac{G(m)_i - d_i}{\sigma_i} \right)^2 . \tag{4}$$

If we let

$$\mathbf{f}(\mathbf{m}) = \begin{bmatrix} f_1(\mathbf{m}) \\ . \\ . \\ . \\ f_m(\mathbf{m}) \end{bmatrix} \tag{5}$$

and $\mathbf{J}(\mathbf{m})$ is the Jacobin matrix,

$$\mathbf{J}(\mathbf{m}) = \begin{bmatrix} \frac{\partial f_i(\mathbf{m})}{\partial m_i} & \cdots & \frac{\partial f_i(\mathbf{m})}{\partial m_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m(\mathbf{m})}{\partial m_1} & \cdots & \frac{\partial f_m(\mathbf{m})}{\partial m_n} \end{bmatrix} \tag{6}$$

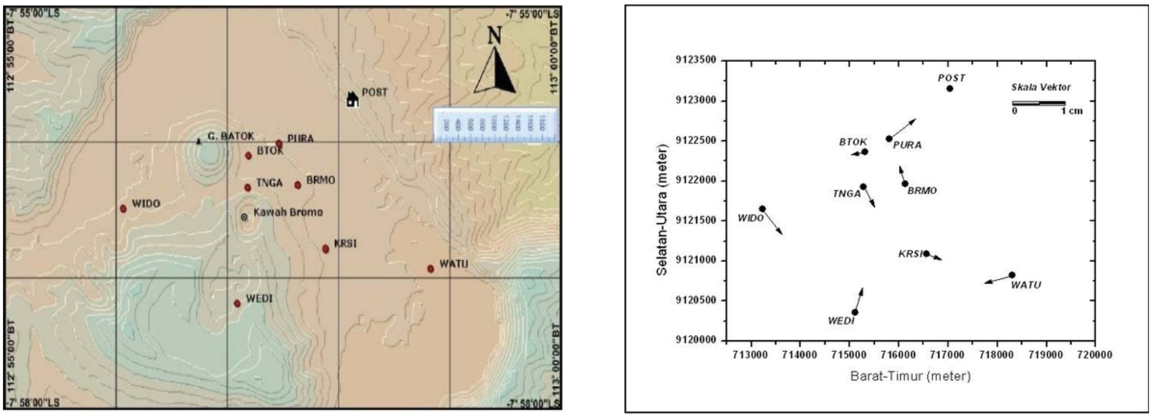
In the Levenberg-Marquardt (LM) scheme,the update of model parameters at *n* iteration is found by solving the equation

$$\left(\mathbf{J}(\mathbf{m}^k)^T \mathbf{J}(\mathbf{m}^k) + \lambda \mathbf{I} \right) \Delta\mathbf{m} = -\mathbf{J}(\mathbf{m}^k)^T \mathbf{F}(\mathbf{m}^k) \tag{7}$$

where λ is a dumping parameter which should be adjusted during the inversion until convergence is achieved.

5. Result and Discussion

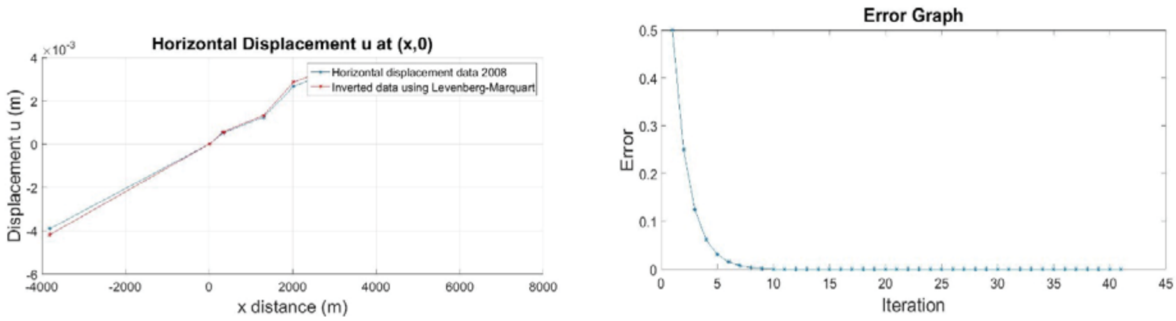
PVMBG has placed several GPS stations at Bromo volcano since 2007. The locations of these stations are shown in Fig. 5a. We use data of deformation recorded at these stations in 2008 published by PVMBG[3].



(a) **(b)**

Figure 5. (a) Coordinate of GPS stations placed at Bromo volcano in 2007. (b) Deformations detected by GPS stations at Bromo volcano in 2008[3]

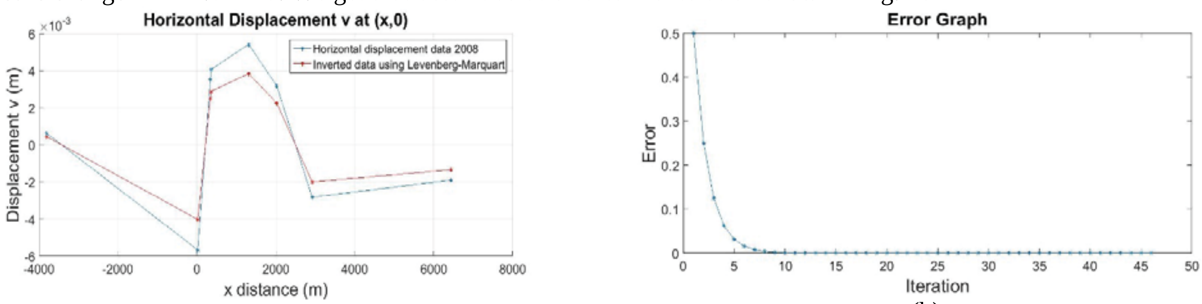
The LM inversion scheme was applied to the 2008 data of deformations recorded at 7 GPS stations. First we tried to reveal models parameter that would be resulted if we used only horizontal displacement components. We get the best fit solution after 41 iteration shown in fig. 6b. It is revealed that the depth of the magma chamber d = 6330.6 m, radius of magma chamber α = 1097.4 m and pressure change $\Delta P \approx 1.0$ MPa. The comparison between the observed and calculated data is shown in Fig. 6a.



(a) **(b)**

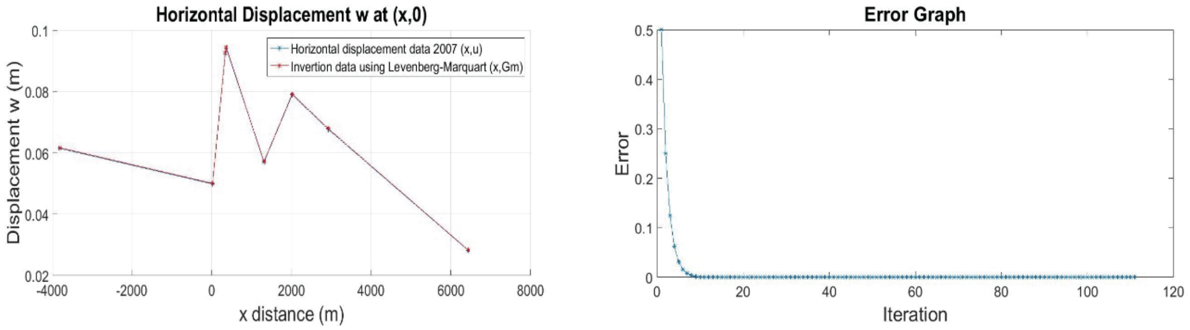
Figure 6. (a) Horizontal Displacement u at (x,0) (b) Error Graph For Horizontal Displacement u at (x,0)

Fig. 7a. depicts the comparison between the observed and inverted data upon using only horizontal displacement data in y-direction. Depth of the magma chamber d = 6308.3 m, radius of magma chamber α = 1098.2 m and pressure change $\Delta P \approx 1.0$ MPa. We get that best fit solution after 46 iteration shown in fig. 7b



(a) (b)

Figure 7. (a) Horisontal Displacement v at (x,0), (b) Error Graph For Horisontal Displacement v at (x,0)



(a) (b)

Figure 8. (a)Vertical Displacement w at (x,0), (b) Error Graph Vertical Displacement w at (x,0)

Implementation of the LM scheme using only vertical components was also conducted and we get that best fit solution after 111 iteration shown in fig. 8b, it is revealed that the depth of magma chamber d = 6307.6 m, radius of magma chamber α = 1098.5 m and the involved pressure change $\Delta P \approx$ 1.0 MPa.

6. Summary

We have used Mogi model to observe deformation of Bromo volcano in 2008. The implementation of Levenberg-Marquardt inversion into the separated horizontal and vertical components of the deformation data suggested that the depth of magma chamber and pressure change in the chamber can be summarized in Table 1.

Table 1. Model Parameters of Displacement

Models	Horisontal displacement u	Horisontal displacement v	Vertikal displacement w
d(m)	6330.6	6308.3	6307.6
a(m)	1097.4	1098.1	1098.5
ΔP(MPa)	1.0	1.0	1.0

It is observed that within the scope of this study the utilization of each component of displacement separately produced almost similar values of model parameters.

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