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Analysis volcano deformation for determining location of the pressure source, hypocentre and magma supply as disaster mitigation efforts: case studies in Merapi volcano

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Analysis volcano deformation for determining location of the pressure source, hypocentre and magma supply as disaster mitigation efforts: case studies in Merapi volcano

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Abstract. Various disaster mitigation efforts due to volcanic earthquakes and volcanic eruptions are carried out to reduce the risk of casualties and damage to infrastructure. One such effort is to conduct volcanic deformation studies. The results of this deformation study include estimating the position of the hypocenter, the pressure source, and the magma supply volume, so that the volume of material released during the eruption can be estimated. With the Mogi Model approach to analysis the Tiltmeter data on the eruption of Merapi Volcano in 2016, the estimated hypocentre is at a depth of about 1,100 to 2,440 m and the depth of the pressure source is about 2,345 m below the peak of Merapi with a magma supply volume of 21.81 million m^3. With the same model approach from GPS data on the 2010 eruption, the results show that the hypocentre is at a depth of about 1,100 to 2,500 m below the peak of Merapi The source of magma pressure is at 2,200 m below the peak of Merapi and the volume of magma supply before the eruption is 15 million m^3. These two results indicate that the depth of the pressure source causing surface deformation originates from shallow magma and is consistent with the seismicity analysis of Merapi in the same period.

1. Introduction

There are 129 volcanoes in Indonesia, which are spread across the islands of Sumatra, Java, Bali, Nusa Tenggara, Maluku and North Sulawesi, one of which is Mount Merapi Volcano [1]. This Mount is basaltic andesite volcanoes which located at 7°32,49' LS and 110°26,40' BT, the highest summit is at 2900 (masl). Merapi has continuously activities that cause the crater and peak to experience deformation which is marked by an eruption [2]. This activity which has lasted for 50,000 years releases material products with an average of 1,000,000 m^3/year [3].

The eruption in 2010 is estimated to be the largest eruption of Mount Merapi with the value of the Volcanic Explosivity Index (VEI) 4. Since the eruption of October 26, 2010 to November 9, 2010 the material released reached 140 million m^3 and even still leaving volcanic material until 2011. The that cause the formation of new lava dome. The eruption that occurred was explosive, several times spewing hot clouds vertically as high as 7 km which could reach far areas up to 17 km from the crater of Merapi, the ashes were spread to Tangerang and Bali with lava reaching more than 20 km to the side west and south. The eruption was not preceded by lava dome formation with a size of 423 mx374 m with a crater depth of 140 m [4,5].

The behavior and characteristics of Merapi Volcano are determined by three main factors, namely the nature of the magma, the internal structure within the volcano and the magnitude of the supply of magma from the depth. The nature of magma that affects the volcanic system of Mount Merapi includes its composition, viscosity level, water content and gas content. While the internal structure in the volcano is very instrumental in determining how the volcano behaves, including how the pipe is magma and the position of the magma reservoir [6]. Merapi Volcano shows fluctuations due to eruptions characterized by lava dome growth followed by proximal eruptions accompanied by pyroclastic flows in the form of melting, lava and hot clouds. There are 2 types of Merapi hot clouds, namely, an avalanche of hot clouds and eruption of hot clouds. The temperature of the hot cloud ranges between 400-600 ° C and the speed reaches 60-70 km/hr [7].

Research on volcanic deformation needs to be continued in order to mitigate disasters due to volcanic eruptions. Eruption is have a high risk for population round the volcano. To minimize the danger, a monitoring continuously is needed for Merapi volcano to find out what kind of mitigation must be done before a volcano disaster occurs. Volcanic deformation monitoring is basically monitoring changes in the surface shape of volcanoes in the form of bloating or contraction caused by volcanic activity. This deformation can be elastic which will return to its original shape when the deformation force is working and usually lies in the aseismic zone and can cause intrusion and extrusion followed by peak eruption. Conversely, plastic deformation does not return to its original form which is usually in the seismic zone active, destructive, intrusion and extrusion seismic zones and causes side eruptions, dooming and also cracking [8].

Volcanic deformation monitoring is usually used to determine the pattern and velocity of volcanic body deformation in horizontal and vertical directions. The data is then combined with data and information from monitoring using other methods, so that it can be used to estimate and reveal the characteristics of magma activity (location of pressure centers) in volcanic bodies and also the volume of magma [9]. Volcanic deformation monitoring can be done regularly or continuously. One method of monitoring carried out continuously is with a tiltmeter [10]. Telemetry is a technique of measuring and observing objects and great distances. Signal information is transformed into other forms that can be poured into the transmission media. The transformation results are converted back into the original signal form [11]. Thus, this Tiltmeter will measure volcanic deformation in the form of the slope of the volcano's body with radians and in the form of inflation (deflation) or deflation (deflation) of the mountain body. Tilt data is one of the information to understand the physical mechanisms in the body of Merapi such as the supply (magma supply) of magma volume and depth of pressure sources.

Volcanic deformation monitoring can also be carried out using the Global Positioning System (GPS) as a method. GPS is a system of satellites, computers and receivers that can determine the latitude and longitude of a receiver on earth by calculating the time difference for signals from different satellites to reach the receiver [12]. GPS is a very effective method of monitoring deformation because the GPS point locations spread out perfectly and depict the entire shape of the volcano. Apart from that, GPS is also considered the most accurate method among the other methods. Apart from the Tiltmeter, the GPS also estimates the magma supply volume and the depth of the volcanic pressure source. The study of the source of pressure and magma supply is expected to help in understanding the characteristics of the internal mechanism of volcanoes which are expected to help predict eruptions and reduce volcanic disasters.

Therefore, this deformation study using a tiltmeter and GPS can monitor changes in the shape of the volcano's body, be it the slope or shift of a point on the volcanic surface. Changes in the shape of this volcano can be in the form of inflation or deflation from the volcano. In this paper, the Tiltmeter method is used to study the deformation of Mount Merapi during the eruption in 2010, while the GPS method is used to study the deformation of Mount Merapi in the 2016 eruption. The calculation model for studying the deformation in the two eruption events is used the Mogi model approach. With this model, the location of the pressure source and the magma supply volume can be estimated. The Mogi model is a computation model that considers the pressure source as a round ball in an infinite elastic space that forms half the space. This model is a calculation model of the results of geodetic measurements of changes in height and horizontal shifts associated with the eruption of Mount Merapi resulting from increased and decreased activity in volcanic magma chambers. This method is still the most widely used method for modeling surface deformation due to decreased or increased activity in the magma chamber.

2. Research Methode

2.1. Tiltmeter data analysis

This study uses tiltmeter data from Plawangan and Babadan station at 7°58,95’ SL, 110°43,19’ EL and 7°52,62’ SL, 110°41,06’ EL which are located at 1,165 msal and 1,321 msal. Data for 2016-2017 period is recorded as tilt and temperature. First position of tools assembly is north direction (Y- axis) and east direction (X-axis), so data must be transformed to radial tangential direction, with rotary transformation angle is 195,7° for Plawangan and 112.9° for Babadan. The result of transformation is calculated and filtered by Origin pro 8 to know the trends of graph and values of anomalies.

The proponent data in this research is seismicity data for 1st October 2016-31th December 2016. Seismicity data includes avalanche earthquake, multiphase earthquake, VTA earthquake, and VTB earthquake. Seismicity data is processed by Seisgram2k and hypo ellipse to find the depth of hypocentre of Merapi volcano.

Mogi models calculation is begun by calculating the distance between monitoring point and crater with each coordinate. The calculation aims to find the value of best fit or the smallest difference between observation value with model value. The result of Mogi modelling will be analyzed and validated with seismicity data of Merapi volcano. Hypocentre calculations are performed on VTA and VTB earthquakes by reading the arrival time of P and S waves on a digital seismogram

2.2. GPS data analysis

GPS data is taken from 4 monitoring stations, 1 station as the main point station (BPPTKG station) and 3 other stations (GRWH, KLAT, DELS) around Mount Merapi as a monitoring station. GPS data in Rinex format is recorded 24 times a day (1 data for each hour). GPS data were taken during 2009 - 2011. Qualitative analysis was carried out by analyzing deformations based on changes in coordinates (degrees) between the Merapi crater and its monitoring stations. The quantitative analysis was carried out by the Mogi models.

GPS data processing using GAMIT/GLOBK software, geocentric and topocentric coordinates come out in GLOBK processing. After that, the deformation is observed as a time series so that the position of the GPS data movement can be known. Mount Merapi deformation can be determined from changes in coordinates between Merapi crater and monitoring stations.

2.3. Mogi Model

Mogi model calculation is begun by calculating the distance between monitoring point and crater with each coordinate. The calculation aims to find the value of best fit or the smallest difference between observation value with model value. The result of Mogi modelling will be analysed and validated with seismicity data of Merapi volcano. Hypocentre calculations are performed on VTA and VTB earthquakes by reading the arrival time of P and S waves on a digital seismogram;

The Mogi source describes the source of a burnt ball that undergoes a change in pressure or a change in volume. The development of the Mogi model has considered the effects of 3D topography and magma pocket effects (nonspherical and non-axisymmetrical). The change in hydrostatic pressure that causes deformation is recorded as the change in the angle of turn in the radial (U_r) and vertical (U_z) components. U_r is the radial shift vector and U_z is the vertical shift vector.

$$U_r = \frac{(1-v)\, a^3 \Delta P}{G}\left(\frac{r}{(f^2+r^2)^{\frac{3}{2}}}\right) \quad (1)$$

$$U_z = \frac{(1-v)\, a^3 \Delta P}{G}\left(\frac{f}{(f^2+r^2)^{\frac{3}{2}}}\right) \quad (2)$$

The change in volcano volume that occurs due to deformation ΔV can be estimated from the value of the k parameter, based on the following equation:

$$\Delta V = 2\pi k \quad (3)$$

$$\Delta V_{injection} = 4\,\pi \;\frac{(f^2+r^2)^{\frac{5}{2}}\delta}{9fr} \quad (4)$$

3. Result and Discussions

3.1. Tilt data analysis

This section will discuss how to make a model of the pressure source causing deformation on the surface based on the slope data from the tiltmeter and validated with the seismicity data of Mount Merapi. Qualitative analysis is carried out by looking at the deformation changes that occur based on the tilt (microradian) data change pattern as a result of observations and quantitative analysis is carried out to see the results of the calculation of the Mogi model based on the existing parameters in the references used so that they match the results of the observations. The qualitative data processing for 2016-2017 produces the biggest anomaly (deflation) period October 2016- December 2016 in Plawangan and Babadan station are $1{,}5\times10^{-5}$ rad and $-5{,}5\times10^{-5}$ rad [13].

To determine the depth of the hypocenter, seismicity data were used as supporting data to validate the causes of surface deformation. Seismicity data on October 2016 - December 2016 shows that there were 9 earthquakes (VTA and VTB), while landslides occurred every day, as many as 29 times. Based on data processing, the depth of the hypocenter based on latitude and longitude during this earthquake period was 2440 m from the peak (Figure 1-2)[13].

Determination of the source of pressure is obtained from the tilt data anomaly through the Mogi model approach. Based on tiltmeter data processing at Babadan Station for the period 2016-2017, there was a deflation of 55.6933 microradian. The input used is the radial distance between the peaks with a tiltmeter (constant), source depth, poisson's ratio, rigidity, pressure source radius and pressure changes. Whereas what is looking for is the horizontal deformation value of the model which has the smallest difference with the observational deformation so that the parameter values in the calculation can be considered correct or describe the actual situation. Mogi modeling is also used to determine whether the deformation of the period is affected by shallow magma sources (magma pockets) or deep magma sources (magma chambers).

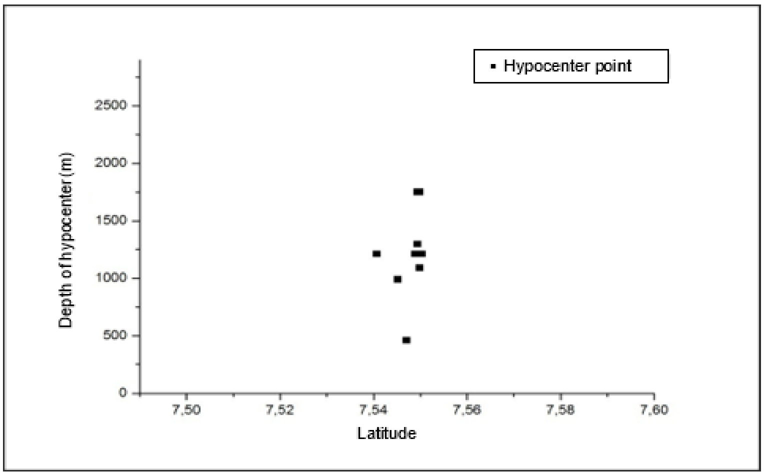

Figure 1. Hypocenter Points Based on Latitude

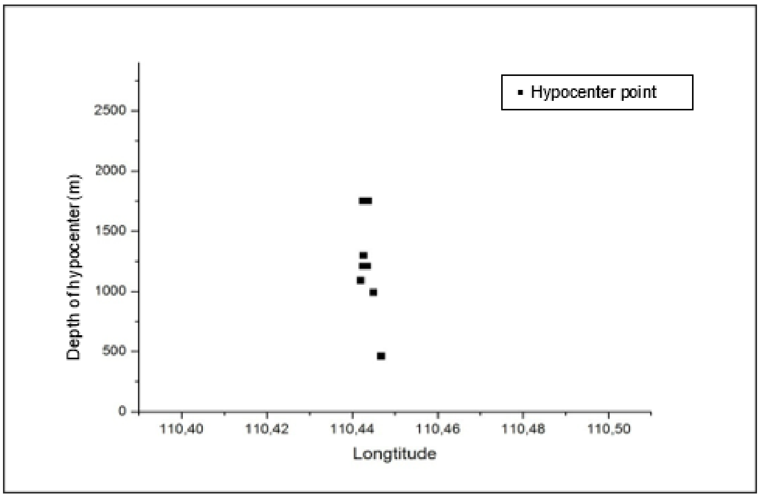

Figure 2. Hypocenter Points Based on Longitude

The data on the tilt angle of the body of the mountain is used to determine the location of the pressure source and the volume of the magma supply that causes the change in tilt. The results of the calculation of the Mogi model for the location of the source of magma pressure that causes deformation are at a depth of 2345.25 m with a change in pressure that causes deformation of 0.1 MPa and the radius of the magma source is 588 m. The processing result data is used as the basis for modeling the magma source.

2D modeling of the magma source made with Surfer 12 based on the topographic map of Mount Merapi with the cross sections A-B (west-east direction) and C-D (north-south direction) and overlaid with the hypocenter points shown in Figure 3-5 below [13]:

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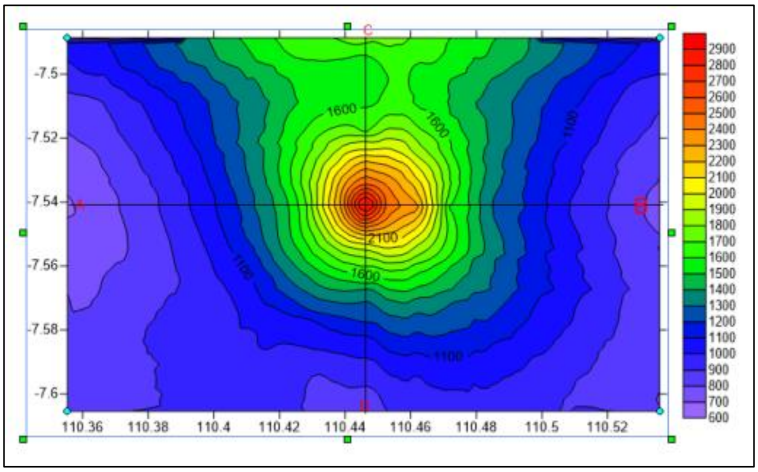

Figure 3. Cross Section of Merapi Topography Map

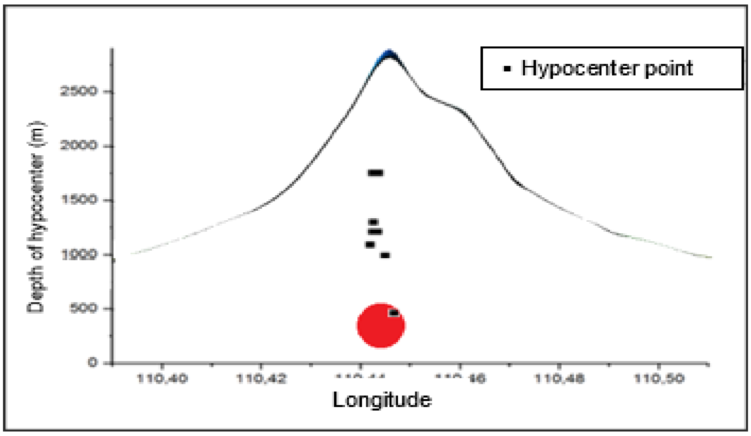

Figure 4. 2D Model between magma source, hypocenter and topography based on longitude (Cross Section C-D)

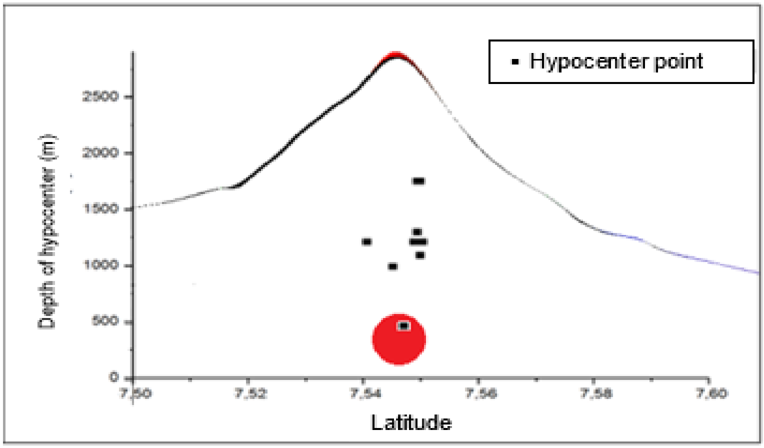

Figure 5. 2D Model between magma source, hypocenter and topography based on latitude (Cross Section A-B)

The density of the magma is different from the surrounding medium which causes the magma to tend to rise. This change in magma supply volume correlates with changes in hydrostatic pressure which can result in measurable deformations on the surface. Through the Mogi model, the magma supply volume can be calculated using equation 4. Based on the tilt data processing at the Babadan station, the magma supply volume value for the period October 2016-December 2016 is 21.81 million m^3.

3.2. GPS data analysis

GPS data were obtained from four monitoring stations consisting of one main station at BPPTKG Yogyakarta and three monitoring stations, namely GRWH, KLAT, and DELS stations. The three monitoring stations are located around Mount Merapi. GPS data in Rinex format is recorded every hour for 24 hours (one day). GPS data was taken from monitoring results from 2009 to 2011. From the GPS data, qualitative analysis was carried out to analyze deformations based on changes in coordinates (degrees) between the Merapi crater and the monitoring station. Quantitative analysis was performed using the Mogi model. This GPS data is then processed using the GAMIT/GLOBK software and the geocentric and topocentric coordinates come out in the GLOBK processing. The observed deformation is a function of time so that the position of the GPS data movement can be determined. Thus the deformation of Mount Merapi can be determined from changes in coordinates between the Merapi crater and the monitoring station.

Deformation due to volcanic activity can be seen from the inflation and deflation processes caused by changes in pressure within the volcano. This pressure change is caused by changes in volcanic activity within the volcano. If magma moves from the bottom up of the volcano, the surface of the volcano is inflationary and becomes bigger than before. This inflationary process led to an elongation of the base line (the distance between the Merapi crater and the monitoring station). If magma moves from top to bottom of the volcano, the surface of the volcano deflates and becomes smaller than before. This deflationary process causes a shortening of the baseline. The deformation activity can also be determined from the height of the monitoring station. If the change is positive, it indicates an inflationary process and if negative indicates a deflationary process [12].

Figures 6, 7, and 8 show the deformation activities of Mount Merapi from 2009 to 2011 obtained from three monitoring stations. From the three figures, it can be seen that the distance between the Merapi crater and the three monitoring stations continues to increase by around +0.01 m to +0.3 m. This means that there was inflation on Mount Merapi and a big eruption at the end of October 2010. After the eruption occurred, volcanic activity finally decreased (deflation). The distance between the crater and the three monitoring stations decreased by approximately -0.001 m to -0.4 m [14].

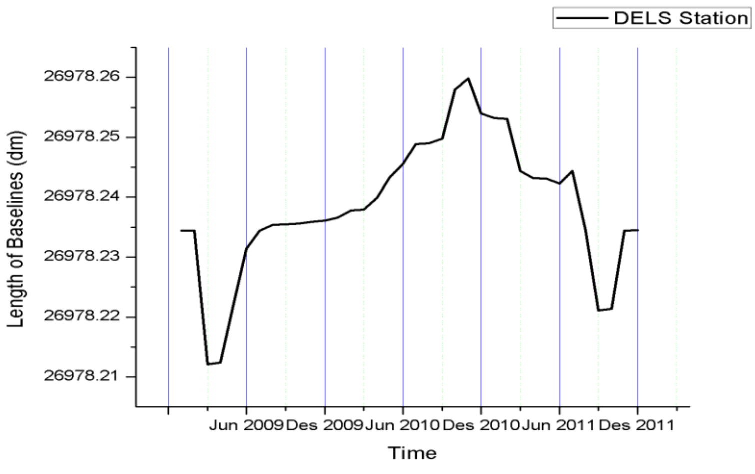

Figure 6. The change of baseline in DELS station

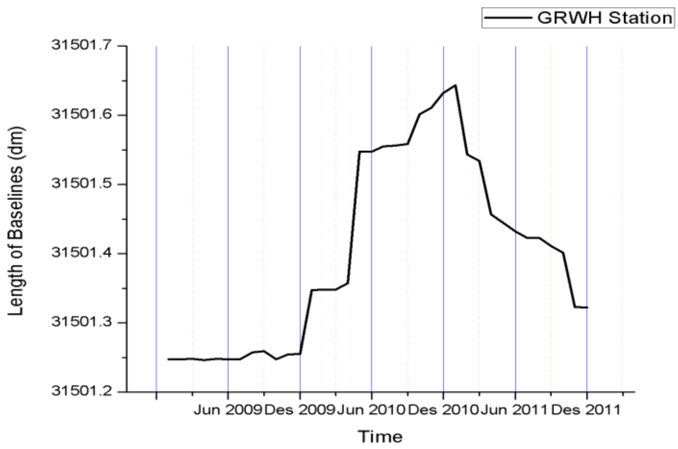

Figure 7. The change of baseline in GRWH station

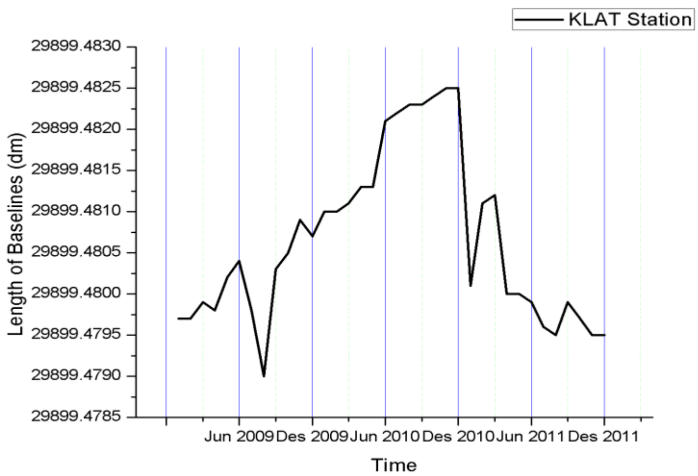

Figure 8. The change of baseline in KLAT station

The increase in volcanic activity leading to eruption can also be seen from the seismicity data. The seismicity of Mount Merapi in 2009-2011 was marked by several VTA, VTB earthquakes and avalanches. For example, during the October 2010 eruption, there were 4 volcanic earthquakes followed by 2 avalanches. This shows that magma is moving towards the surface. The pressure of magma below the surface causes volcanic earthquakes and avalanches. Volcanic earthquake data can be used to determine earthquake hypocenter. If the depth of the earthquake is between 0 - 1.5 km it is called VTB (Shallow Volcanic-Tectonic) and the depth is between 2.5 - 5 km the earthquake is called VTA (Deep Volcanic-Tectonic) [15].

Seismicity data obtained from Seismogram2K is then processed by Hypoellips so that the latitude, longitude, and depth of the hypocenter can be known. Figure 8 shows the depth of the hippocenter points during the 2010 eruption in 3 D.

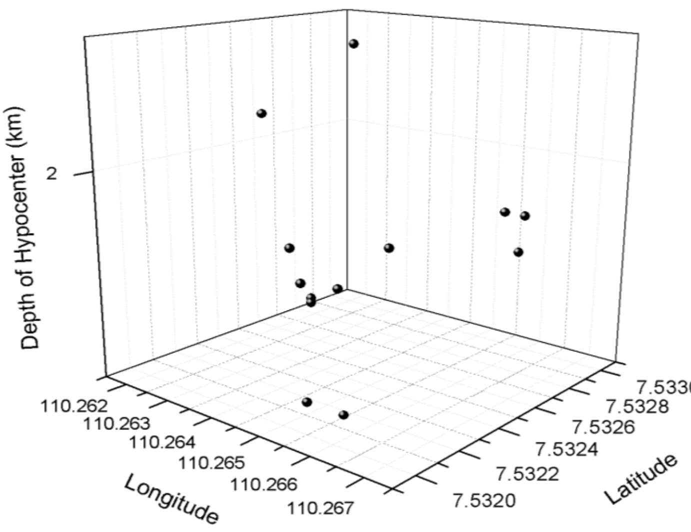

Figure 9. 3D model of the hypocenter's depth during eruption 2010

Based on the qualitative analysis, each GPS chart of the DELS, GRWH, and KLAT stations shows significant deformation. GPS data anomaly in 2009-2011 is -0.4 meters to +0.4 meters. This anomaly can be used to calculate and determine the location of the source of magma pressure and the volume of magma supply under the surface of Mount Merapi. The assumption used is that the source of magma pressure causes the surface of the volcano to change, be it inflation or deflation. The results showed that the location of the source of magma pressure was still in the magma pocket, and even some shallow volcanic activity occurred. In addition, inflation in the body of Mount Merapi indicates that volcanic activity has suppressed the volcano's body. Mogi Model calculations show that the depth of the pressure source is 2,200 m or 2,2 km below the peak of Mount Merapi.

The change in the volume of the magma supply is considered to be related to the change in hydrostatic pressure at a pressure source. The density of magma is different from the surrounding medium, so the magma tends to rise to the surface. This change in the supply volume of magma can result in measurable deformations on the surface. With the Mogi model, the magma supply volume can be calculated using equation 4. Based on GPS data processing, the results at DELS and KLAT Stations do not really show the deformation that occurred in the 2009-2011 period so that the calculation of the magma supply volume in that period is calculated based on the processed model at GRWH Station. From the calculation of the Mogi model, the value of the magma supply volume for the period before the eruption is 15 million m^3.

The results of seismicity analysis during the eruption period from October to December 2016, which showed the deepest hypocenter depth of 2,440 m and calculations with the Mogi model from the tilt data where the magma source was at a depth of 2,345 m showed that the location of the magma pressure source was in accordance with the location of the magma pocket. This zone is characterized by a flaccid zone at a depth of 1.5-2.5 km below the peak interpreted as a magma pocket, while the location of the magma chamber is estimated to be at a depth of more than 5 km. The results of this study The results of this study also indicate the suitability of the hypocenter depth with the position of the magma source model. Similar results were also obtained from seismicity data in the eruption period of October 2010, which showed a hypocenter depth between 2,100 - 2500 m with the location of the magma source based on intimate GPS data at a depth of 2,200 m. This research's result is same if compared with the last research with depth of magma source is 2000-3000 m below the summit, and the radius of magma chamber is 1000 m [16].

4. Conclusion

Deformation in the period October - December 2016 indicates that deflation has formed at Mount Merapi with anomaly of 1.5 E-05 rad for Plawangan station and -5.5 E-05 rad for Babadan station. From Mogi calculations from tilt data, the location of the magma pressure source is at a depth of 2,345 m below the peak of Merapi which is in line with the hypocenter depth at 2440 m below the peak of Merapi. From the calculation of the Mogi model from the tiltmeter data, it is also obtained that the magma supply volume which causes the surface deformation of Merapi is 21.81 million m^3. In the 2010 eruption, there was also deformation of the body of Mount Merapi, which was indicated by the extension of the base line (inflation) between the crater and several monitoring stations of Mount Merapi. The baseline extension is around +0.001 meters to +0.3 meters and after the eruption it shortened (deflation). From this deformation data, with the MOGI model, the estimated depth of pressure sources before the 2010 eruption was 2.2 km, the volume of magma supply before the 2010 eruption was 15 million m^3**.**

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