Gravity observation data analysis 1988 -1998 - 2011 to determine gravity changes of Merapi volcano

R D Indriana¹, ², S B Kirbani³, A Setiawan³ and T A Sunantyo⁴

¹Geophysics Department Doctoral Programme FMIPA UGM, Yogyakarta, Indonesia
²Geophysics Department FSM UNDIP, Semarang, Indonesia
³Geophysics Department, FMIPA UGM, Yogyakarta, Indonesia
⁴Geodesy Department, FT UGM, Yogyakarta, Indonesia

*Corresponding author: rina_dei@yahoo.com

Abstract. The big eruption of Merapi Volcano in 2010 resulted in a Merapi-type eruption being a phreatic type that is thought to be the result of subsurface changes. The study of gravitational gravity change in observational data of gravity observation in 1988, 1998, 2011 was conducted to determine the sub-surface changes of Merapi pre and post-eruption of 2010. The research data consisted of primary and secondary gravity data provided by Geophysics Laboratory Department of Physics Gadjah Mada University in Yogyakarta consisted of g observation data in 1988, 1998, 2011 and Data Digital Elevation Model (DEM). The result of this study is the relative terrestrial g_observation of 1998-1988 around the peak of Merapi is -85 s.d. 70 mgal, in the northwest and north of the peak is -15 s.d. - 55 mgal, east and west worth 5 s.d. 15 mgal and south of peak anomaly change is -5 s.d. 0 mgal. The relative gestation of the relative terrestrial observations of 2011 on relative terrestrial g_observations in 1998 showed changes in patterns around the peak of Merapi. The value of terrestrial observation g relative changes 2011-1998. The relative value of terrestrial g_observations change is -85 s.d. 70 mgal, northwest -5 s.d. - 20 mgal, east and west peaks 0 s.d. 10 mgal, in the southern peak of Merapi there is an anomaly value change -5 s.d. -50 mgal. The pattern of contour change has been compatible with the Merapi eruption mass distribution map 1911 s.d. 2006 and DEM changes.

1. Introduction
Merapi is an almost persistently active basalt to basaltic andesite volcanic complex in Central Java (Indonesia) and often referred to as the type volcano for small-volume pyroclastic flows generated by gravitational lava dome failures then whole-rock geochemical data allow a reassessment of the geological and geochemical evolution [1,2]. Bignami et al. [3] propose a novel approach for pyroclastic density currents (PDC) volume estimation following the 2010 Merapi eruption. The analysis has been done to estimate the PDC deposit extent and thickness that covers the south flank of the volcano.

Eruption of Mount Merapi volcano in 2010 released 150 million m³ of volcanic material which is estimated to result in changes of subsurface structure and mass movement as the process of filling the Merapi reservoir, and the peak morphological changes of Merapi Volcano in the form of Garuda peak collapsed until Merapi crater is open (200 m wider). Lava mobility (distance traveled vs. difference in
height from source to end of deposit) at Merapi eruption is greatly controlled by their initial velocity, mass and height of generation (potential energy) and efficiency of conversion from potential to kinetic energy (loss of momentum due to frictional processes both within the current and at current edges) Charbonnier and Gertisser [4-6]. Changes in eruption activity in the form of phreatic eruption occurring several times in 2013 and 2014.

The peak change of Merapi appears as shown in Figure 1, post-eruption 2010 resulting in a wide crater measuring 432 m × 374 m, there is also a 303 m fracture crack and a new 140 m depth crater. At the bottom of the new crater there is a new lava dome that is the source of the phreatic eruption.

Figure 1. Changes in the peak of Merapi Source: BPPTKG, 2014.

Changes occurring after the eruption of Merapi can be done through observation of structural changes and changes in the gravity field of Merapi continuously, so that can be obtained a general description of the structure and characteristics of volcanic material from time to time so that the possibility of activities that will occur in the future can be estimated.

The study was conducted to find out the changes of the local Bouguer and Geoid anomaly values in Merapi volcano pre and post-eruption 2010 to examine changes in subsurface structure and changes in the mass distribution of Merapi. Preliminary research was conducted to obtain pre and post-eruption g_observation values in 2010, using g_observation data in 1988, 1998 and 2011.

1.1 Basic principles of gravity
The method of gravity is Newton's law of attraction between the particles. Newton's law states that the pull force between two particles and the mass apart from the center of its mass is proportional to the multiplicity of the mass with and inversely proportional to the square of its distance. The force is described as follows.

\[
\vec{F}(\rho) = -G \frac{m_0 m}{|\vec{r} - \vec{r}_0|^2} \times (\vec{r} - \vec{r}_0)
\]

In which is the force acting on by itself and having a direction opposite to the direction, ie, from toward (Telford, 1999).

1.2 Gravity observation (g_obs)
The large g_observation readable result of field measurement conversion influenced tool height, tidal and drifted (Torge, 1989). Mathematically can be written in the form of equations

\[
g_{obs}(x, y, z) = g_{mgal}(x, y, z) - TA(x, y, z) - PS(x, y, z) - D(x, y, z)
\]
With \( g_{\text{obs}}(x, y, z) \) is the value of \( g_{\text{observation}} \) on the topographic surface, \( g_{\text{mgal}}(x, y, z) \) is the reading of gravity values in mgal, \( TA(x, y, z) \) tool correction, \( PS(x, y, z) \) Tidal correction, and \( D(x, y, z) \) drift correction.

### 1.3 Changes to \( g_{\text{observation}} \)

Changes in the data \( g_{\text{observation}} \) 2011 to \( g_{\text{observation}} \) in 1998 and \( g_{\text{observation}} \) data 1998 to \( g_{\text{observation}} \) data 1988 done with the confidence

\[
\Delta G_{1\text{obs}}(i,j) = g_{\text{obs 2001}}(i,j) - g_{\text{obs 1998}}(i,j)
\]
\[
\Delta G_{2\text{obs}}(i,j) = g_{\text{obs 1998}}(i,j) - g_{\text{obs 1988}}(i,j)
\]

The analysis is done to get the contour pattern.

### 1.4 Sites

The study was conducted in an area of approximately 27 km \( \times \) 27 km, with a limit of 7.70 LS s.d. 7,450 LS and 110.30 BT s.d. 110.60 east. The research area covering Mount Merapi to the northern boundary is Kab. Semarang, east of Boyolali and Sukoharjo District, the south is Kodya Yogyakarta and Kab. Klaten and the west is Magelang District.

Gravitational data used consisted of primary and secondary data. Primary data is data of measurement result in 2011 s.d. 2012 with the amount of gravity data available as much as 200 data. Secondary data from gravity measurement in 1986 s.d. 1989 [7-9] and gravity data of 1997 s.d. 2000 [10,11]. The initial amount of data of 1997 s.d. 2000 as many as 230 data and in 1986 s.d. 1989 as many as 123 data. Other key data are GPS data and DEM data. GPS data was used in 1998 and 2011 data, but the 1988 data uses Pauli altimeter data and USGS maps (Figure 2).

![Figure 2. Location of research and distribution of data points. □ data 1988, Δ data 1998, and ○ data 2011](image)

2. Methods

The change of gravity is obtained through continuous or periodic observations at the same point so that the required data at the same point from time to time are obtained. In this study, the process of change is done by area by comparing the changes of a contour over time. From this analysis of changes, it is desirable to obtain an overview of subsurface changes such as the possibility of the direction of mass movement, as a subsurface overview over time. In the contour monitoring process,
the data used is the observed gravity field and elevation/elevation data. The gravity field monitoring anomaly is obtained from two gravity values. Monitoring process for the period 1997 s.d. 2000 is a reduction of the gravity field anomaly value of 2000 to 1997 s.d. 1999. The monitoring process 1988 s.d. 1989 is done if possible because it is worth noting the change in elevation value. The process of measuring the elevation at that point of accuracy is less accurate because of the level of accuracy of the tool when it is still low. For contour, change process can be done by comparing contour change in 1988, 1998 with 2011.

3. Result and discussion
The result of data processing in the form of g_observation value then mapped. The contour map of g_observation in 1988, 1998 and 2011 as shown in Figure 3 and Figure 4 has the same unequal area of research to make adjustments to the boundaries of the research area.

Anomalous contour pattern is a high-value observation in the southern part of the study area and decreases to the north. The main pattern of the contour no change alleged no change in the subsurface regional structure.

Figure 3. Contours 1988, 1998 and 2011 (-the 2011 gravity data contour, - contours of gravity data 1998, and - contours of 1988).

Contour map of anomaly g_observation 2011 show distribution value 977652.394 mgal s.d. 978155.433 mgal. Merapi peak area g observation of minimum value that is 977652.394 mgal s.d. 977781.2 mgal (Figure 4).

Figure 4. Map contour g_observation 2011 data and measurement stations

Figure 5. Map contour g_observation data 1998

Figure 6. Map contour g_observation 1988 data
Contour map of anomalies $g_{\text{observation}}$ 1998 show distribution value 977602.539 mgal s.d. 978150.226 mgal. The peak area of Merapi is worth a minimum of 977602.539 mgal s.d. 977793.289 mgal (Figure 5). Contour map of anomaly $g_{\text{observation}}$ 1988 showing distribution value 977578.630 mgal s.d. 978154.850 mgal. Merapi peak area is worth a minimum $g_{\text{observation}}$ that is 977578.630 mgal s.d. 977812.720 mgal (Figure 6).

| Table 1. $g_{\text{obs}}$ value |
|-------------------------------|
| year | $g_{\text{obs}}$ max (mgal) | $g_{\text{obs}}$ min (mgal) |
|------|-----------------------------|-----------------------------|
| 88   | 978154.850                  | 977578.630                  |
| 98   | 978150.226                  | 977602.539                  |
| 11   | 978155.433                  | 977652.350                  |

From the observation of general observational values (table 1), it is known that the value of $g_{\text{obs}}$ in Merapi in 2011 is higher than in 1998 and 1988. The change in $g_{\text{observation}}$ value is about -85 s.d. 70 mgal (Table 2). From table 2 it is known that the changes in $g_{\text{observation}}$ 2011 - 1998 are greater than the 1998 - 1988 data changes. With the large eruption mass not causing the value of $g_{\text{observation}}$ to decrease.

| Table 2. $g_{\text{obs}}$ value changing |
|----------------------------------------|
| year | $g_{\text{obs}}$ max (mgal) | $g_{\text{obs}}$ min (mgal) |
|------|-----------------------------|-----------------------------|
| 1998-1988 | 45                  | -85                  |
| 2011-1998 | 70                  | -45                  |

The distribution of changes in $g_{\text{observation}}$ values can be observed in Figure 7 and Figure 8. From Figure 8 and Figure 9 there appears to be a major change at the top of Merapi and around the peak of Merapi.

Changes in data $g_{\text{observation}}$ 2011 to $g_{\text{observation}}$ data 1998 showed a maximum change in the peak of Merapi north of 15 mgal s.d. 65 mgal and the minimum value in northwest and south and north of Merapi peak at -15 s.d. -45 mgal. Average $g_{\text{observation}}$ change -5 s.d. 5 mgal (Figure 7).
Changes in data \( g \) observation 1998 to the 1988 data showed a change in contour pattern in the peak area, with the distribution of \( g \) observation value north and northwest of the peak of Merapi of -25 mgal s.d. -65 mgal. East, south and peak land of Merapi change the value of \( g \) observation of 5 s.d. 45 mgal. Average \( g \) observation change -5 s.d. 5 mgal (Figure 8).

The change in contour pattern of the observed \( g \) observation when compared to the Merapi mass distribution map shows the conformity of the pattern (Figure 9), so it is possible that one that changes the \( g \) observation value is the increase of mass on the surface.

Merapi undergoes significant post-eruption topographic changes in 2010. The topographic changes when mapped are as shown in Figure 10. On the map, there appears to be an increase in topographic value on the northern peak and a decrease in the southern peaks and to the southwest.

Change the value of DEM -130 m s.d. 40 m is concentrated at the top and spreads around the peak of Merapi to the south to the west. The change to -130 m to the south of the peak leads to the southwest. Topographic changes are expected due to the collapse of Garuda peak which causes the \( g \) observation value at the top of Garuda to decrease. The change of DEM to the north of Merapi peak at 40 m corresponds to the change of \( g \) observation 2011 - 1998 by 15 s.d. 65 mgal. So one possible cause of the change in \( g \) observation value is the topographic changes as a result of mass increase and decrease of mass on the surface.

For a more comprehensive analysis, it is necessary to conduct further research to determine the changes in subsurface mass distribution.

4. Conclusion
The value of \( g \) data observations 1988, 1998 and 2011 have similar contour patterns of change occurring in the peak areas and around the peaks. If the pattern of changes in \( g \) observation values is observed, then there is a supposition of the value of \( g \) observation because of the mass increase on the surface that is around the peak of Merapi after the eruption.

References
[1] Gertisser R, Cassidy N J, Charbonnier S J, Nuzzo L and Preece K 2012 *Nat. Hazards* 60 623
[2] Gertisser R, Charbonnier S J, Keller J and Quidelleur X 2012 *Bull. Volcanol.* 74 1213
[3] Bignami C, Ruch J, Chini M, Neri M, Buongiorno M F, Hidayati S and Sayudi D S 2013 *J. Volcanol. Geotherm. Res.* 261 236
[4] Charbonnier S J and Gertisser R 2011 *Sedimentology* 58 1573
[5] Charbonnier S J and Gertisser R 2012 *J. Volcanol. Geotherm. Res.* 231 87
[6] Charbonnier S J, Germa A, Connor C B, Gertisser R, Preece K, Komorowski J C, Lavigne F, Dixon T and Connor L 2013 *J. Volcanol. Geotherm. Res.* 261 295
[7] Wahyudi 1986 Gravity investigation on Merapi Volcano (Yogyakarta: UGM Press) p 136
[8] Wawan G A K 1985 Heavy anomaly air gravity analysis of Merapi and surrounding Volcanoes (Yogyakarta: UGM Press) p 122
[9] Koulakov I, Maksotova G, Jaxybulatov K, Kasatkina E, Shapiro N M, Luehr B G, El Khrepy S and Al- Arifi N 2016 Geochem. Geophys. Geosystems 17 4195
[10] Setiawan A. Modeling of Gravity Changes on Merapi Volcano: Observed Between 1997-2000 (Doctoral dissertation Darmstadt: Technischen Universität Darmstadt)
[11] Carr B B, Clarke A B and Vitturi M D 2018 Earth Planet. Sci. Lett. 482 377