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# Analysis of gravity changes in 2016 Pidie Jaya Earthquake

**Zahra Ayisha, Agus Setyawan*, Udi Harmoko, Jatmiko Endro Suseno**
Department of Physics, Faculty of Science and Mathematics, Universitas Diponegoro, Semarang, Indonesia
**Corresponding Author:** agussetyawan@fisika.fsm.undip.ac.id

## Abstract
An earthquake occurred in Pidie Jaya on December 7 2016 with a magnitude of 6.5 and a depth of 15 km at 05:33 WIB. Based on data from BMKG, the position of the epicenter is at coordinates 5,250 N – 96,240 E. The research was carried out using gravity anomaly data from the GRACE Satellite with a period from 7 November 2016 to 7 January 2017. The 2016 Pidie Jaya earthquake resulted in changes in gravity anomaly values around the epicenter of the earthquake because it was a shallow and large-magnitude earthquake. This research aims to determine the pattern and magnitude of the change in the value of the temporal variation gravity anomaly around the epicenter due to an earthquake using the GRACE satellite and to determine the pattern of change in the temporal variation gravity anomaly associated with the earthquake mechanism and conditions below the earth's surface around the earthquake epicenter. The contouring results show that there was polarization on December 11, 2016. Then the value of the difference in the gravity anomaly also shows a change, the biggest change being the difference on day 4: December 3, 2016, and December 11, 2016, at the 7$^{th}$ point with a value of 1.582845 mGal. The smallest anomalous change is found on the difference between day 24, namely November 13, 2016, and December 31 2016 at point 7 with a value of -0.000595 mGal. These changes are assumed to be caused by the activity of the Sipopok/Simalanga fault which is influenced by the activity of the Eurasian and Indo-Australian plates as well as changes in land surface height. Around the epicenter of the earthquake, there is a low gravity anomaly pattern with the rocks forming surface deposits composed of fluvial and sand deposits.

**Keywords:** Gravity, Free air, Bouguer, GRACE satellite, earthquake, Pidie Jaya Aceh

## Introduction
Earthquakes are sudden natural events that occur due to the movement of tectonic plates below the earth's surface. Such earthquakes are called tectonic earthquakes [1]. Geographically Indonesia is in an area with a very complex tectonic plate order, therefore Indonesia often experiences natural disasters such as earthquakes. Indonesia is flanked by 3 major tectonic plates namely the Eurasian Plate, Indo-Australian Plate, and Pacific Plate, and 1 micro Philippine Plate [2]. A major earthquake hit the Reuleut area, Pidie Jaya on December 7, 2016. The earthquake with a magnitude of 6.5 M occurred at 05:33 WIB with epicenter coordinates 5,250 LS - 96,1240 BT and a depth of 15 km. The earthquake was classified as a large earthquake. Large earthquakes are expected to cause changes in the value of gravity anomalies due to changes in the density of rock masses below the earth's surface due to sudden movements of tectonic plates. This study utilizes the gravity method between time or gravity micro time-lapse with the 4th dimension is time to determine changes in the value of gravity anomalies that are assumed to occur due to earthquakes. GRACE is a gravimetric satellite in collaboration with NASA and DLR with missions that can provide observational data over long timescales to monitor large-scale mass changes [3]. GRACE satellite research was conducted on crustal dilation after the Sumatra-Andaman earthquake in 2004 [4].

## GRACE Satellites (*Gravity Record and Climate Experiment*)
The gravity method is a method based on measuring variations in the gravitational field on the earth's surface, there are many researchers have applied the gravity method. In the current era, a complete method for measuring gravitational field data from satellites has been developed, including data on the geographic location of measuring points on the Earth's surface [5, 6, 7]. GRACE (Gravity Record and Climate Experiment) launched on March 17, 2002, in Russia is a gravimetric satellite system in collaboration between DLR (Deutsches Zentrum fiir Luft-und Raumfahrt) in Germany and NASA (National Aeronautics and Space Administration) in the United States [8]. The GRACE satellite provides monthly forecast data of global gravity fields on scales of hundreds of kilometers or more [9]. The technique from GRACE is to read changes in the Earth's gravity field by monitoring changes in distance that occur between pairs of two GRACE satellites in orbit. In carrying out its mission, the GRACE satellite will record data from an altitude of 400 km above the Earth's surface to describe temporal variations in gravity to the dynamic mass of Earth's water and ice [10].

## Gravity Micro Time Lapse
The microgravity method between time is an extension of the three-dimensional gravity method by involving the fourth dimension, time [11]. It is referred to as micro because the anomalous value produced is very low on the micro Gal (μGal) scale. The principle of the inter-time gravity method is to measure iteratively both daily, weekly, monthly, and yearly.

$$\Delta g(x,y,z,\Delta t) = \Delta g(x,y,z,t_2) - \Delta g(x,y,z,t_1)$$

Where $\Delta g(x,y,z,\Delta t)$ is a microgravity anomaly between times, $\Delta g(x,y,z,t_2)$ is a late Bouger anomaly. And $\Delta g(x,y,z,t_1)$ is an early Bouger anomaly.

## Earthquake

An earthquake is an earth vibration caused by the release of an acceleration of energy in which the energy is released in various directions from the center of the source [12]. The explanation of process of earthquakes was explained by an American seismologist named H.F. Reid in 1906 who stated that rock deformation that occurs in the lithospheric layer results in the release of elastic strain energy of rocks below the earth's surface.

Convection currents arise from the heating process of the Earth's core in certain places, then the current rises to the surface and spreads horizontally. The plates will continue to move because of the presence of very large charged currents. The current is generated from the temperature difference between the upper and lower earth membranes so that the membrane moves. The membrane is under a large tectonic plate consisting of various types of rocks such as silicate compounds that fuse partially or completely. This membrane is not liquid but is sticky and soft and has a very high pressure. Charged currents arise because the membrane tries to move its material to the top, this can cause a difference in thickness between the bottom layer and the top layer of the earth's membrane.

The layer of membrane is thick enough that some parts will drop to hotter temperatures below and this process occurs continuously without stopping from the past. The earthquake that occurred in Pidie Jaya was centered at 5.25°N and 96.24°E close to the sea but the earthquake did not cause a tsunami. The earthquake occurred on Wednesday 7 December 2016, measuring 6.5 M and 15 km deep. This earthquake event was not preceded by an initial earthquake (foreshock) but there were several aftershocks. This earthquake was generated by a horizontal fault (strike-slip).

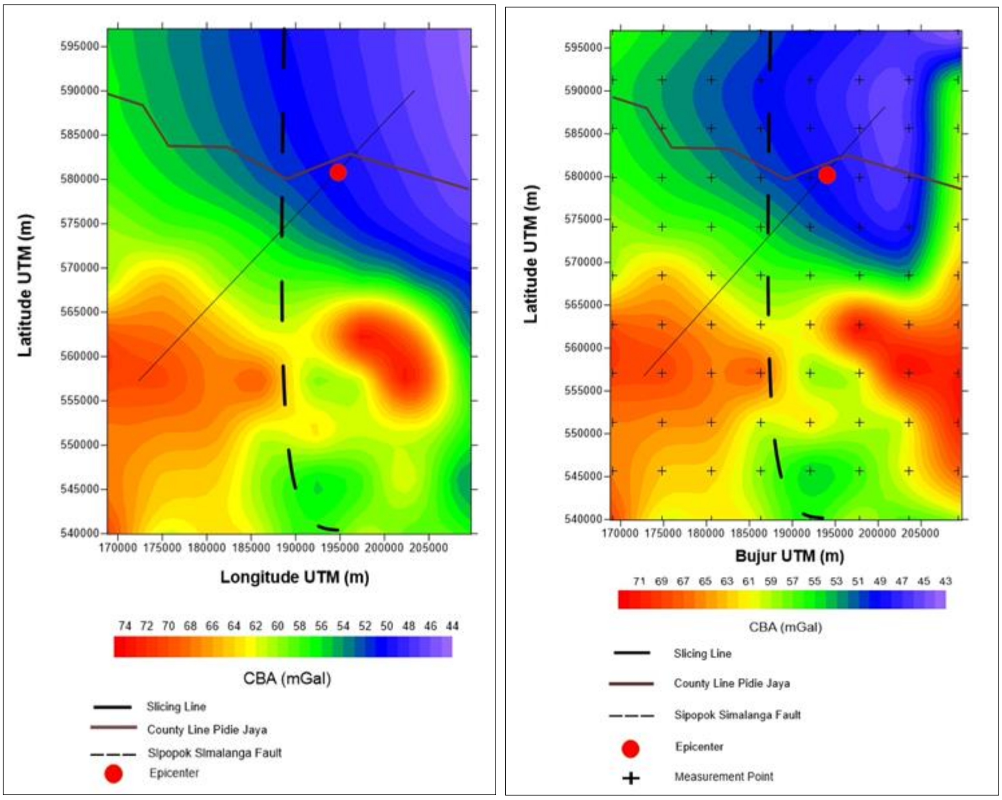
## Methods

GRACE satellite data was obtained through the http://icgem.gfz-potsdam.de/calc website. The data obtained is in the form of longitude coordinates, latitude, and daily anomaly values that have been corrected to Simple Bouger Anomaly (SBA) and elevation values. Furthermore, topographic data is obtained from https://earthexplorer.usgs.gov/. Topographic data is processed in the Global Mapper software for further calculations to obtain CBA data. Then SBA, elevation, and topography data are processed in Oasis Montaj software to get Terrain correction. Next, perform calculations in Microsoft Office Excel software to obtain Complete Bouger Anomaly (CBA) data and changes in gravity anomalies. The value of the CBA anomaly is made into an anomaly contour map with Surfer software. Furthermore, a cut was carried out through the epicenter to identify the CBA value around the epicenter of the earthquake. Then analyze the results obtained with the geological conditions of the 2016 Pidie Jaya earthquake incident area

## Results and Discussion

Polarization anomalies are not as visible on anomalous contour maps for the period of 5 days before the earthquake to 3 days after the earthquake. The displacement of rock density below the surface of the earthquake area temporally has a small dimensional size to the microgal scale (μGal) causing the pattern of change not so visible [13]. The anomalous polarization began to appear on the 4th day after the earthquake. Figure 1(a) shows the zones with high anomalies are located in the Southeast and Southwest of the study area with a value range of 65 -71 mGal. The high anomalous zone flanks the Sipopok/Simalanga fault. Zones with low gravity acceleration anomaly values on the map are shown in purple to turquoise with a value range of 44-54 mGal indicating the density or density of rock masses in the Northeastern part of the epicenter of small earthquakes. The moderate gravity acceleration anomalies are shown in green to yellow with a value range of 54-64 mGal which indicates the density or density of rock masses in the Southeast and Northwest epicenters of medium-sized earthquakes. For high gravity acceleration, anomalies are indicated in orange to red which indicates the density or density of rock masses in the Southwest part of the epicenter of large earthquakes. Figure 1(b) shows the polarization of the anomalous value of gravity acceleration. The epicenter of the earthquake was in an area with relatively low anomalies ranging from 48-52 mGal, low anomalies were also mapped in the Strait of Malacca and the Eurasian Plate zone. While the high anomalous value is in the Indo-Australian Plate zone. The Eurasian Plate has a low density and tends to move toward the Northeast, while the Indo-Australian Plate has a greater density and so tends to move towards the North. This shows that the density associated with the value of gravity correlates with the Indonesian tectonic plate. The high anomalous zone is also located in the southwest epicenter of the earthquake which is the Sipopok/Simalanga fault zone and leads to the Sumatran fault zone. Active faults can generally cause tectonic deformation due to the relatively strong movement of the two fault blocks due to faults that are at the boundary of low and high anomalous zones. The negative anomalous zone is around the epicenter of the earthquake where the anomaly is associated with low density.

The low density of the rock would be consistent with the shallowness of the fault because from the magma most of the water would come out [14]. This is by the parameters of the Pidie Jaya earthquake which has an earthquake depth of 15 km and is classified as a shallow earthquake. In the zone around the epicenter, the earthquake has lithological conditions in the form of surface deposits composed of fluviatile and sand deposits. The deposit has a boundary between the organic layers that fall on it. Fluvial deposits are rock units that have a quaternary (Holocene) age or youngest. The deposits are composed of sand, clay, silt, and gravel resulting from wave and river activities. Fluviatil or alluvial deposits have loose to solid properties and have a low to moderate level of water escape.




(a) (b)

**Fig 1:** Map of anomalous contour (a) 4 days before the earthquake, (b) 4 days after the earthquake

Figure 2 shows that the anomaly value was relatively stable on the day before the earthquake then on December 11, 2016, the anomaly decreased and that day was the day with the lowest anomaly value. On December 12, the anomalous value was again recorded as relatively stable until December 17, 2016. Then it is noted that the anomalous value at point 7 is the point with the highest anomalous value and point 3 is the point with the lowest anomalous value that occurs in all days. Figure 3 is a graph of the daily CBA anomaly value at point 5 except December 11, 2016. This is done to see the pattern of changes in the value of gravity anomalies of temporal variations at the nearest point of the epicenter of the earthquake. Anomaly values increased from November 7 to November 16, 2016, with an increase of 0.000368 mGal. The anomalous value was recorded to have decreased relatively until 3 days before the earthquake, on December 2, 2016.

The increase in the value of this gravity anomaly occurs due to an increase in the density of subsurface rocks around the anomalous value decreased by 0.000237 mGal starting 3 days before the earthquake, namely December 4, 2016, to 1 day before the earthquake, namely December 6, 2016. Then the relative anomaly value increased after the earthquake until December 15, 2015. The anomaly value decreased again until December 21, 2016, and was recorded to increase relatively again until December 31, 2016. Then the anomalous value fell until January 3, 2017, and was relatively stable until January 7, 2017. Based on Figure 2, there is an anomaly that is at its lowest on December 11, 2016, which was recorded at 47.136276 mGal at point 3. Anomalous changes that occur can be caused by variations in mass distribution below the earth's surface or by changes in land level in the area. In taking data on that day, a fixed set of density or density is used so that the possibility of anomalous changes occurs due to changes in land surface height or topographic variations in the study area.

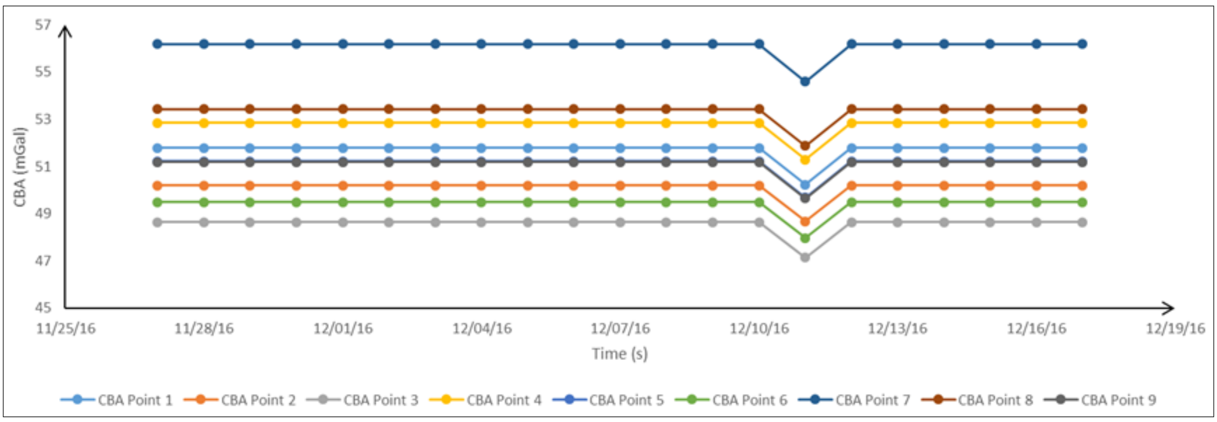



**Fig 2:** Graph of CBA values of the 10-day range around the epicenter of the earthquake

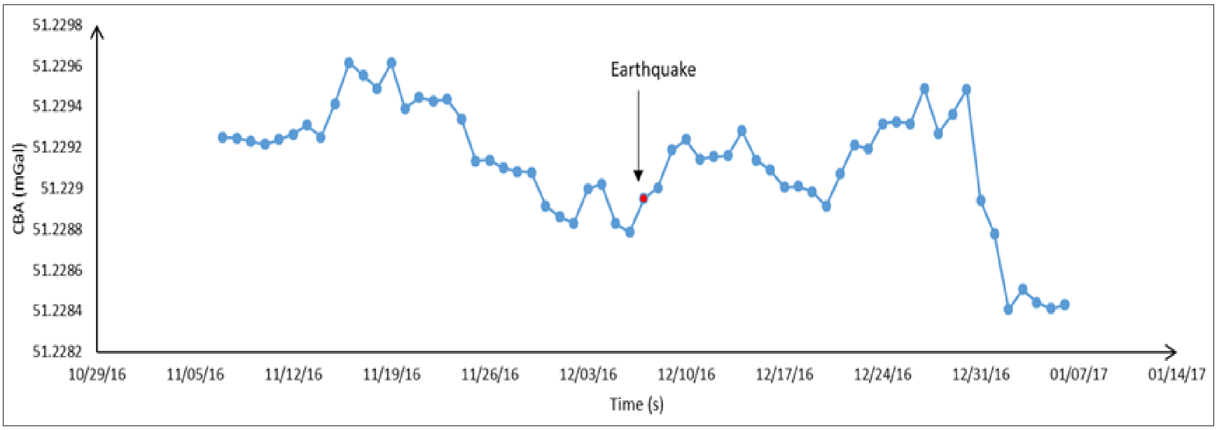



**Fig 3:** Graph of the daily value of CBA at point.

In general, local gravity anomalies are caused by tectonic fault activity so there is a correlation between faults and changes in gravity. Along active faults will appear regional gravity anomalies and have an intense positive-negative gravity anomaly change gradient [15]. Intense gravity anomalies change gradients occur in most large-magnitude earthquakes, but gradients will differ depending on the location of the earthquake and the characteristics of the active fault. This is to the parameters of the 2016 Pidie Jaya earthquake where the earthquake was a relatively large earthquake with a magnitude of 6.5 M. Changes that occur in the crust or deformation of the earth's fault occur due to movement in the fault which can cause the subsurface density of the fault to also change [16].

According to previous research, intense gravity anomalies would have appeared along active faults before an earthquake. This is due to the condition of the Sumatra region which experienced further deformation before the 2016 Pidie Jaya earthquake, namely after the 2004 9.2 M Aceh earthquake occurred. In large faults and have smaller densities, it implies that the fault contains water or gas fluid. A small density means that it has a low density. The low density of the rock correlates with shallow faulting because magma will eject most of the water fluid at depths of less than 1 km. As a result of the process of going in and out of the fluid to the fault area, it can cause changes in rock density in the area. Changes in density that occur can also be caused by plate activity. The Eurasian plate hitting the Indo-Australian plate can cause mass accumulation in the earthquake event area, resulting in changes in the acceleration value of gravity anomalies in the study area.

## Conclusions

The earthquake that occurred in Pidie Jaya in 2016 with a magnitude of 6.5 M and a depth of 15 km resulted in changes in gravity anomalies that were detected by the GRACE satellite. The gravitational anomaly in the one month before the earthquake was recorded to have decreased relatively and experienced a change of 0.00046367 mGal. The gravitational anomaly within 1 month after the earthquake was recorded to have relatively increased with a change of 0.00048654 mGal. The changes are thought to be caused by the activity of the Sipopok/Simalanga fault which is influenced by the activity of the Eurasian and Indo-Australian plates as well as changes in land surface height. Around the epicenter of the earthquake, the earthquake had a low gravity anomaly pattern with a value range of 48-52 mGal, the rocks of which are surface deposits composed of fluvial deposits and sand which are of Quaternary (Holocene) or youngest age. These deposits are composed of sand, clay, silt and gravel resulting from wave and river activity which have loose to dense properties and have low to moderate water release.

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