Gravity Survey in Pandan Mountain – East Java, Indonesia

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Abstract. Pandan Mountain is volcanic area located near Kendeng Zone in East Java, Indonesia. Pandan Mountain area, that becomes one of geothermal prospect in East Java, was impacted an earthquake event with 4.2 Richter’s scale on 25th June 2015 (10:35 AM local time). In this study, we conducted gravity survey in Pandan Mountain area to understand density subsurface. Data acquisition and processing are describe in detail to provide gravity anomaly map in this study area. The gravity anomaly then transformed into frequency domain to provide depth estimation of subsurface sources. We conducted subsurface modeling to find the interface density between hot-volcanic intrusion (modeled with low density) and background rock of pyroclastic layer (modeled with high density). The preliminary results of 2.5-D gravity inverse modeling shows that trend of low density distribution in the subsurface found in the deeper depth for Northern part of study area. Subsurface model of study area provide asimmetric shape of hot magma intrusion. The model solution of interface density suggest the possibility of magma source from Southern part of study area.

1. Introduction

An earthquake with the magnitude 4.2 Richter’s scale occured on Thursday, 25 June 2015 (10:35 PM local time) causes several damages to 57 houses in Dusun Pohulung. As reported in the previous study [1], the event relocate in the coordinate 7.6305°LS and 111.7529°BT with 14.81 km focus depth. This unexpected earthquake indicate that tectonic in Kendeng Zone still active. Sinistral fault that close to this area is slicing Pandan Mountain from North-East is related with the earthquake [2]. Pandan Mountain (location shown in figure 1) is administratively situated as the border of three cities: Madiun, Nganjuk, and Bojonegoro.

This area also interesting to studied because Pandan Mountain area is identified as one from eleven geothermal prospect in East Java [3]. Ministry of Energy and Mineral Resources of Indonesia also mentioned Pandan Mountain area as working area for geothermal exploitation in the decission No: 2774K/30/MEM/2014. Geothermal system in this area was identified by hot water with temperature in the surface about 35°C [4].

Researchers from geophysical engineering of ITB start to conduct field survey using gravity and passive seismic in 2016. General objective of the study is to understand related tektonic/volcanic activities, so we start with preliminary study and preparing sufficient data. In this paper we will report the documentation of the activity in Pandan Mountain from gravity data acquisition, processing, and modeling.
2. Geology Setting
Volcanic region in Java island related with subduction of Indian-Australian plate from the South that subducted beneath Eurasian plate. Based on Setijadji work [2], depth of the slab that subducted beneath East Java is decreases from Lawu Mountain (about 175 km) to Semeru Mountain (about 150 km). Geology structure that developed in this area is strike-slip and thrust faults. Two major faults in Pandan Mountain mentioned by Thoha [5] are Gedibal and Pacul Fault.

There are folds with East-West trend can be found in the North of Pandan Mountain [6]. Pandan Mountain lies within Tertiary fold belt, across which folded strata are apparently offset and warped [7]. The pattern of Kendeng folds structure in Pandan Mountain symmetrically deflected. The pattern that can be seen in the East and West side of Pandan Mountain can be caused by deviation of local compression stress from the present of magma chamber Pandan Mountain in the South [8].

Simplified surface geology map for this study is shown in figure 2. There are faults and folds pattern located in NE and NW of Pandan Mountain. We can see ten formations identified in (15x16) km square of geology map in figure 2, there are Kerek Formation, Kalibeng Formation, Atasangin Member, Klikit Formation, Sonde Formation, Pucangan Formation, Kabuh Formation, Intrusive Rocks, Pandan Breccia, and Notopuro Formation.

3. Gravity Data Acquisition
Before survey, gravity team prepared gravimeter from ITB campus. Gravimeter scintrex CG-5 records from previous activity (9-10 March 2016) was checked and analyzed. The records data were used in simple calculation (as shown in CG-5 manual book) and then we get 1.421 as the new drift drift constant of CG-5 (SN-815). Simulation in the campus then conducted (24-26 May 2016) to get statistical estimation for new drift constant performance. Linear drift estimated up to -0.058 mGal/day.
Survey activity in Pandan Mountain conducted from 27th to 30th May 2017. Reference value of gravity survey tied using loop scheme from Bandung-Cepu-Madiun-Bandung. During this activity, we need to enter coordinate value as tidal parameter into CG-5 for each city coordinate (Bandung, Cepu, and Madiun). Team mobilisation from Bandung to Cepu (around 430 km) traveled about 10 hours by train. Local mobilization from Cepu to Pandan Mountain area (about 52 km) traveled by rent car for 2.5 hours.

We have several locations as reference for relative gravity survey in Bandung and Cepu. For this survey, we use three locations that already observed using absolute gravimeter A-10 in 2013 and 2014 (publication related with this data survey can be found in Setyawan et al. [10] and Nishijima et al. [11]). Simple data processing to tied-up reference gravity value with absolute gravimeter data in our study area (BSK station) involving 392 sample. Statistically, gravity observation in BSK station is shown in figure 3 and then we use average value from the sample as reference value for survey in Pandan Mountain (978089.285 mGal).

![Figure 3](image3.png)

**Figure 3** Histogram and statistic descriptive from gravity observation in Base Klangon (BSK) station.

During 4 days survey with relative gravimeter in Pandan Mountain, gravity team observed 93 stations with distribution shown in figure 4. One station observed in BSK and the other 92 stations located in main road and tracking route of Pandan Mountain. Onsite processing conducted each day after the survey consist of drift and tidal correction for 92 stations respect to reference value in BSK. Table 1 shows summary of data acquisition from CG-5 records during survey activity in Pandan Mountain.

### 4. Gravity Data Processing

After we get variation of gravity observation for each station, next step we conducted density estimation using Nettleton’s method [12]. For density estimation, we select NW-SE section (shown in figure 4) as slice line of gravity anomaly and topography variation. Range of density value from 1.5 to 3.0 g/cc were computed to provide 12 gravity anomaly (Complete Bouguer Anomaly /CBA).

Visually, CBA and topography correlation is shown in figure 5. Quantitatively we compute 12 correlation coefficient from 12 CBA curve and 1 topography curve. Correlation coefficient value are in the range of -0.397 to 0.247. We select to use CBA value with density input that provide coefficient correlation close to zero. Correlation coefficient value -0.040 that resulted between CBA curve (density 2.1 g/cc) and topography curve became our result for density estimation.
Table 1 Summary of gravity survey in Pandan Mountain area.

| Survey        | 2016 |
|---------------|------|
| Date          | 27-30 May |
| Gravimeter    | CG-5815 |
| Good Leveling | 98.16% |
| Auto Rej. > 5%| 7.77%  |
| Stnd. Deviation > 0.1 | 22.29% |
| Average drift | -31 μGal |
| #Day(s)       | 4   |
| #Reading(s)   | 489 |
| #Observation(s) | 93  |

Figure 4 Gravity stations distribution overlaid with elevation data at Pandan Mountain.

CBA calculation for 92 stations in Pandan Mountain then corrected using density 2.1 g/cc for Bouguer correction (BC) and terrain correction (TC). For this study, CBA calculated using following formulation:

\[
CBA = g_o - (g_o - (0.3086 \times h) + BC - TC),
\]

where \(g_o\), \(g_o\) are gravity observation, theoretical gravity (International Gravity Formula 1980), and station’s elevation to calculate free-air, BC, and TC. Since this paper were presented in 2017, the CBA map for this study only corrected with inner zone of terrain correction. Just side note for next publication, our recent CBA value already corrected with more proper terrain correction.

CBA map then produced using gridding calculation from 92 gravity stations in Pandan Mountain area. Separation of target anomaly from CBA in this study area is conducted using moving average method based on spectrum analysis. Spectrum analysis can be provided after we transform CBA grid to frequency domain through Fast Fourier Transform (FFT). Fourier’s transform from vertical component of gravity field \(F[g_z]\) is described by Blakely [13] as follow:

\[
F[g_z] = 2\pi\gamma\mu e^{ik(z_0 - z')}, \\
\]

where \(\pi\), \(\gamma\), \(\mu\), \(e\), \(k\), \(z_0\), and \(z'\) respectively are mathematical constant (ratio of circle’s circumference to it’s diameter), universal gravitational constant, mass of the body, mathematical constant (Euler’s number), wave number, elevation of gravity station in the surface, and depth body in the subsurface. Natural logarithmic from FFT amplitude \(F[g_z]\) then provide the following equation:

\[
\ln A = \ln F[g_z] = \ln 2\pi\gamma\mu + \{|k|(z_0 - z')\}.
\]
Figure 5 Comparison of visual correlation between 12 CBA curve and topography curve. CBA (with density 1.5 - 3.0 g/cc) plotted with orange dot plot and topography with blue plot.

Figure 6a shows CBA grid with interval (Δx and Δy) 100 m. We will use CBA data from figure 6a as an input of 1-D FFT. FFT computation needs $2^n$ data for each line, so we select 38 slice lines of S-N and 43 slice lines of W-E. To represent study area, 81 FFT output (ln A values) is averaged and plotted as spectrum in figure 6b. Three trends that shown in the spectrum give depth estimation for anomaly source (for 1833, 192, and 35 meters) based on gradient value of line equation.

Target anomaly in this study is expected in the range of wave number trend II. Target anomaly will be separated from trend I and III using two steps of moving average filter (in spatial domain). Moving average in spatial domain is involving several data in certain range of window ($N$). Window is decided from the value of $k_{\text{cut-off}}$ that set as a border between rejection-band and pass-band. Window value can be calculate using following equation:

$$N = \frac{2\pi}{k_{\text{cut-off}} \Delta x^2}. \quad (4)$$

First filter output (with high-pass) using $N=5$ is an anomaly that reject the spectrum in the range of wave number <0.002. The output from first filter then filtered again (with low-pass) using $N=31$ to provide an anomaly that reject the spectrum in the range of wavenumber > 0.013. Comparison contour of CBA and target anomaly is shown in figure 7. CBA map (figure 7a) has value in the range of 49 to 73 mGal, while target anomaly map (after separated from higher and lower frequency) has value in the range of -8 to 3 mGal (figure 7b). Target anomaly resulted from filtering process in this study area is expected to reduce regional effect and noisy data in the surface.
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**Figure 6** (a) Illustration of 38 slice lines of S-N and 43 slice lines of W-E from CBA grid in study area as FFT input, (b) average spectrum (k vs lnA) from 81 calculation.

**Figure 7** Comparison contour map between (a) CBA and (b) target anomaly.

5. **Gravity Data Modeling**

In this section, we describe subsurface model of inverse problem using illustration as seen in (figure 8). We adapt the design of sedimentary with iterative calculation by Chakravarthi [14]. The subsurface model consists of M-series juxtaposed vertical prism. Vertical series of subsurface model placed below each gravity stations (N-series data). Two layers of vertical prism below each gravity stations represent two density contrast in the subsurface (homogeneous background density ($\rho_1$) and low density of hot magma ($\rho_2$)).

Each vertical prisms has length in 3D cartesian coordinate system (dx, dy, and dz). The lower bound of vertical series in the subsurface model are limited with certain depth, while the upper bound of vertical series in the subsurface model are limited with tophographic. Interface for each vertical series (between $\rho_1$ and $\rho_2$) are representation of our subsurface structure that will be updated as our solution. In order to reach best data miss-fit we used iterative calculation of minimizing differences between observed ($g_{\text{obs}}$) and calculated ($g_{\text{cal}}$) data. Iterative calculation attempt to modify model solution ($z(j)$). Model solution is updated using slight modification from previous study of Chakravarthi [14], as follow:

$$z^{(k+1)}(j) = z^{(k)}(j) + \frac{\text{Rand} \times (g_{\text{obs}}(j) - g_{\text{cal}}(j))}{\gamma \rho_1}.$$
Where $i$, $j$ and $k$ respectively denotes index number of data observation, index number of vertical series in subsurface model, and the number of iteration. The procedure of iterative calculation described with program flow-chart as seen in figure 9. Random number (Rand), universal gravitational constant ($\gamma$), and background density ($\rho_1$) used as nominator and denominator in the equation (5) in order to provide rough estimation of updated solution. Flow-chart of the program will be described in several steps. Start from the input, initialization, initial model, iterative process (update model, well constraint, miss-fit evaluation), stoping criteria, and output.

![Figure 8 Illustration of subsurface model to explain background density intruded by hot magma (low density).](image)

**Figure 8** Illustration of subsurface model to explain background density intruded by hot magma (low density).

![Figure 9 Flow-chart of the program to seek model solution of interface density in volcanic area.](image)

**Figure 9** Flow-chart of the program to seek model solution of interface density in volcanic area.

**Input** of the program consist of three categories:

1. Gravity data observation and station coordinates. In this category, program will accomodate information related with station’s interval, target anomalies, $N$-obs data, and instrument height from the surface.

2. Subsurface model parameters. In this category, we can accomodate following information: well data, well location/coordinate, depth estimation from spectral analysis, M-vertical series of prism, length of body strike in axis-Y direction, coordinat prisms, maximum depth for subsurface model, sedimentary layer density, and basement density.

3. Iterative parameters for maximum iteration number and realization number for statistical purpose.
Initialization of the program used to introduce:
1. Default constants (universal gravitational constant, unit conversion, prism’s index).
2. Empty matrix as storage space of objective function (data miss-fit), calculated \(g_{cal}\), and model solution.

After initialization, next step from the program is generating initial model and several calculation (Kernel matrix, \(g_{cal}\), and miss-fit). Initial model can be generated as random interface, flat interface, bowl shape interface, subjective initial model based on user interpretation. Forward calculation for calculated data uses equation of gravitation caused by 3-D polygonal prism body with numeric expression as described by Plouff [15].

Iterative process to update model solution for each vertical series is following mathematic formula of equation (5). If we have information from well data, we can accommodate in iterative process (as well-constraint). After model solution in well location is tied-up, the program calculates Kernel matrix, \(g_{cal}\), and miss-fit. Miss-fit evaluation will do comparison between current and previous model. Miss-fit evaluation only accept downhill changes of the objective function (miss-fit).

Stopping criteria the iterative process is set-up using maximum iteration number. If maximum iteration number is met, we get model solution as our output. The program working with random number, so it is possible we will get different solution as realization. We can evaluate deviation of solution based on statistical point of view from several realization.

Density contrast as an input of background density \((\rho_1)\) in this study area are is +0.10 g/cc, while density contrast as an input of low density \((\rho_2)\) is -0.20 g/cc. Strike length body (in the Easting axis) as an input of iterative calculation is 5 km, while length interval in the Northing axis of subsurface model is 100 m. Maximum depth (in the z-axis of subsurface model) are set-up in 10 km. Total 86 vertical series of subsurface model calculated below 86 data input. Data input are topographic and filtered anomaly with 100 m interval data in the direction of S-N azimuth (sliced exactly in centre part of study area).

Miss-fit data for model solution had been minimized over 100 iteration. The miss-fit data changes over the iteration number shown in figure 10. Comparison between observed and calculated gravity data shown in figure 11. Based on the results in figure 12, we get simplified subsurface structure as an interface between body \(\rho_1\) and body \(\rho_2\).

![Figure 10 Miss-fit data changes over iteration number.](image)

In this study, we also calculate inverse modeling using GRAV3D (academic version). The program was developed by UBC-Geophysical Inversion Facility. The problem addressed by GRAV3D involves grid data of gravity caused by a 3-D distribution of density contrast within the volume beneath the survey area. The subsurface volume is modeled as a set of rectangular cells each with constant density contrast. Brief description of the program are explained by Li and Oldenburg [16].
Figure 11 Comparison between observed (dot plot) and calculated data (line plot).

The set-up of GRAV3D inversion for this study is limited for density contrast value in the range of +0.20 to -0.20 g/cc. We plot negative density contrast value from inverse results in the S-N section and then overlayed with the interface density results from figure 12. Figure 12 also shows comparison model from our solution and GRAV3D model. Both model results provide similar trend of negative density depth in the subsurface. The trend of interface density is located deeper in the Northern part of study area. This results also similar with quick modeling from previous study (Santoso et al.[17]).

Figure 12 Comparison subsurface model between interface density and GRAV3D along S-N section in study area.
6. Summary
Iterative calculation using gravity data can be used to estimate the interface density contrast in the subsurface between background density and low density (possible interpretation for hot magma). Real data application using gravity data in Pandan Mountain area provide the model asymmetric shape of hot magma intrusion.

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