Subsurface structure of Tangkuban Parahu area derived from CSAMT and gravity investigation

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Abstract. An integrated Controlled-source audio frequency magnetotelluric (CSAMT) and gravity investigations across the Tangkuban Parahu area has been carried out. The Tangkuban Parahu is located in Bandung, West Java, one of a volcano area. The purpose of investigations was to locate the subsurface structures of the area that may correlate to a geothermal reservoir in unknown geothermal potential area. The CSAMT survey has been conducted in the area using transmitter located in 3-5 km from the survey area. The objective of the survey was to determine a subsurface resistivity structures. On the other hand, the gravity survey was carried out in the same sites with the CSAMT sites. The results of the integrated interpretation of the CSAMT and gravity data show that the subsurface of the area has a correlation with a geothermal reservoir structure. It is also confirmed by several surface manifestations in the Ciater area, the north of the Tangkuban Parahu volcano.

1. Introduction
Tangkuban Parahu is located in Bandung, West Java, Indonesia. The topographic elevation of the field is ranging from 800 to 2200 m above sea level. An integrated Controlled-source audio frequency magnetotelluric (CSAMT) and gravity investigations across the Tangkuban Parahu area has been carried out. The aim of the CSAMT method is to determine a subsurface resistivity structure, while the aim of gravity method is to determine a subsurface density structure according to a different gravitational value in a measurement point.

The CSAMT measurement, in the operating frequency range of 0.25 Hz to 8192 Hz, has been carried out in the area using transmitter that located about 3 to 7.5 km in the South from the sounding site area to acquire 42 soundings with the irregular space stations, varied from 200 to 500 m between sounding, covering the Tangkuban Parahu and its environs. On the other hand, 42 sites of the Gravity survey using gravity meter was carried out in the same sites with the CSAMT survey. The location survey Parahu is located in a volcanic region in Bandung, West Java, Indonesia. The field in UTM (Universal Transverse Mercator) zone 48 is geographically situated between 790,000 – 795,000 East and in the range of 9,200,000 – 9,257,000 North. The topographic elevation of the field is ranging from 800 to 2200 m above sea level (figure 1).

The objective of the CSAMT and Gravity Surveys were to determine subsurface structures of the area based on resistivity and density characteristics. These characteristics can be used to define whether there is a geothermal prospect in unknown geothermal potential area or there is no prospect. Furthermore, if it is possible in the future, the area can be exploited to produce a geothermal energy for generating the electricity after doing several geophysical, geological and geochemical exploration. For the reason, the geothermal energy is one of the alternatives in Indonesia.
2. Basic Theory

2.1. Basic Theory of CSAMT method

The basic concept used in the CSAMT method can be derived from the solution of Maxwell’s equations, these are

\[ \nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad (1) \]
\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (2) \]
\[ \nabla \cdot \mathbf{D} = 0 \quad (3) \]
\[ \nabla \cdot \mathbf{B} = 0 \quad (4) \]

where \( \mathbf{E} \) is the electric field intensity (V/m), \( \mathbf{B} \) is the magnetic induction (tesla), \( \mathbf{H} \) is the magnetic field intensity (A/m), \( \omega \) is the angular frequency, \( \mu \) is the magnetic permeability (H/m).

The apparent resistivity on the earth surface derived from Maxwell’s equation in a far-field zone is

\[ \rho_{axy} = \frac{1}{\mu \omega} \left| \frac{E_x}{H_y} \right|^2 \quad (5) \]

In this paper, a 2D inversion technique based on a non-linear conjugate gradient method [3] was applied to invert the selected CSAMT data.

2.2. Basic Theory of Gravity method

Gravity method is one of the geophysics methods to determine a subsurface density structure based on a different gravity value on measurement point. The method is one of passive methods because there is nothing sources inducting to the earth surface when the measuring is occurred. Gravity method utilized difference between gravity values at each measurement points. There are factors that affected these values such as difference in rocks’ density beneath the surface, earth’s tides, latitude angle, sea surface height, topography, and others. Therefore, several corrections are needed to obtain the real gravity value where it can only interpret the value of subsurface density. The Newton’s Gravity Law can be expressed as follows:

\[ F(r) = G \left( \frac{m_1 m_2}{r^2} \right) \hat{r} \quad (6) \]
where $\mathbf{F}$ is the force between $m_1$ and $m_2$, $m_1$ is the mass of object 1, $m_2$ is the mass of object 2, $r$ is the distance between objects’ centres, $G$ is the gravitational constant and $\hat{r}$ as unit vector [4].

3. Interpretation

3.1 Interpretation of CSAMT data

Employing a 2D inversion scheme to the CSAMT data in Tangkuban Parahu, we constructed the 2D resistivity section for several profiles. The resistivity section obtained from 2D inversion of Line-3 indicates that the distribution of the low resistivity anomaly (<10 ohm.m) in the depth of 700-1000 m is distributed in the northeast from t-19 to t-28 (figure 2). This anomaly may considered as hydrothermal alteration zone in a geothermal reservoir structure. On the contrary, the low resistivity anomaly is not found in the southeast. From the figure also shows that the electrical discontinuity is found below the sounding site t-07, it may correspond to the existing fault in the area [1].

![Figure 2](image1.png)

Figure 2. Resistivity section derived from 2D inversion result at Line-3.

![Figure 3](image2.png)

Figure 3. Resistivity section derived from 2D inversion result at Line-8.

Figure 3 shows 2D resistivity section of Line-8 from Northwest to Southeast direction, the distribution of the low resistivity anomaly is also found below sounding sites t-17 to t-35. It is also considered as the hydrothermal alteration zone. On the other hand, figure 4 shows 2D resistivity section of Line-9 from Northwest to Southeast direction, it indicates that the subsurface resistivity of this line is mainly composed of 3 layers. The first layer (overburden) is high resistivity (50 to 500 ohm-m) that is between 800 to 1000 meters thick. These anomalous features may be due to faulting, fracturing, and hydrothermal alteration along the significant fault.
3.2. Interpretation of Gravity data

Measurement of gravity method in this survey used a Lacoste Romberg gravimeter that measuring different gravitational value at each measurement points caused by differences in rock density beneath the earth’s surface. The value of gravity is also affected by factors such as earth’s tidal, latitude angle, and others. Therefore, corrections such as drift correction, tide correction, latitude correction, free-air correction, Bouger correction, terrain correction and complete Bouger correction are required to obtain the real gravity value where it can only interpret the value of subsurface density. Gravity data correction results are presented in the complete Bouger anomalies contour with values varying between 369-395 miligal shown in figure 5. The high anomalously values are conformed to high rock densities while the low anomalously values are indicated with the low rock densities, this area is predicted as a source of geothermal potential.

Figure 4. Resistivity section derived from 2D inversion result at Line-9.

Figure 5. Contour map of Complete Bouger Anomaly.
The anomalies will be separated into two categories such as the residual and regional anomalies. Both anomalies will be modeled by slicing the residual contour maps shown in figure 6 (in miligal). From the residual anomaly contour shows that the average density value of 2.44 g/cm³.

![Figure 6. Contour map of residual anomaly with cross-section.](image)

Using software using GRAV2DC modelling [5] for cross-section of Line 3 with the direction from Southwest to Northeast, it is confirmed that the density contrast varies between -0.1 gr/cm³, 0 gr/cm³ and 0.065 gr/cm³ (figure 7). The created model has a depth of 0-3 km with an error of 2.73% generating a variety density as shown in table 1.

![Figure 7. Result of subsurface modelling from Line 3.](image)

**Table 1. Interpretation from line 3.**

| Number | Depth (km) | Contrast Density (gr/cm³) | Density (gr/cm³) | Interpretation |
|--------|------------|---------------------------|------------------|----------------|
| 1      | 0.52 - 2.3 | 0.065                     | 2.505            | Andesite       |
| 2      | 1.2 - 3    | -0.100                    | 2.34             | Rhyolite       |
| 3      | 0 – 1.5    | 0                         | 2.44             | Andesite       |
Cross section of Line 8 is a direction from Northwest to Southeast resulting a variety density contrast between 0 gr/cm$^3$, -0.1 gr/cm$^3$, -0.06 gr/cm$^3$ and 0.065 gr/cm$^3$ (figure 8). The created model has depth of 0-3 km with an error of 1.52% generating a variety density is shown in table 2.

![Figure 8. Result of subsurface modelling from Line 8.](image)

**Table 2.** Interpretation from line 8.

| Number | Depth (km) | Contrast Density (gr/cm$^3$) | Density (gr/cm$^3$) | Interpretation |
|--------|------------|-------------------------------|---------------------|----------------|
| 1      | 0 – 3      | 0                             | 2.44                | Andesite       |
| 2      | 0.01 – 1.6 | 0.065                         | 2.505               | Andesite       |
| 3      | 1 – 3      | -0.100                        | 2.34                | Rhyolite       |
| 4      | 1.15 - 3   | -0.060                        | 2.38                | Rhyolite       |

Finally, the Line 9 is sliced from Northwest to Southeast, producing variety densities between 0 gr/cm$^3$, -0.1 gr/cm$^3$, -0.06 gr/cm$^3$, 0.1 gr/cm$^3$ and 0.0651 gr/cm$^3$ (figure 9). The created model has depth of 0-3 km with an error of 1.52% generating variety densities as shown in table 3.

![Figure 9. Result of subsurface modelling from Line 9.](image)

| Distance (m) | Gravity Value (m Gal) | Depth (m) |
|--------------|------------------------|-----------|
| 0.0          | 1.15                   | 0.0       |
| 0.1          | 1.12                   | 0.1       |
| 0.2          | 1.11                   | 0.2       |
| 0.3          | 1.11                   | 0.3       |
| 0.4          | 1.10                   | 0.4       |
| 0.5          | 1.09                   | 0.5       |
| 0.6          | 1.08                   | 0.6       |
| 0.7          | 1.07                   | 0.7       |
| 0.8          | 1.06                   | 0.8       |
| 0.9          | 1.05                   | 0.9       |
| 1.0          | 1.04                   | 1.0       |
| 1.1          | 1.03                   | 1.1       |
| 1.2          | 1.02                   | 1.2       |
| 1.3          | 1.01                   | 1.3       |
| 1.4          | 0.99                   | 1.4       |
| 1.5          | 0.98                   | 1.5       |
| 1.6          | 0.97                   | 1.6       |
| 1.7          | 0.96                   | 1.7       |
| 1.8          | 0.95                   | 1.8       |
| 1.9          | 0.94                   | 1.9       |
| 2.0          | 0.93                   | 2.0       |
| 2.1          | 0.92                   | 2.1       |
| 2.2          | 0.91                   | 2.2       |
| 2.3          | 0.90                   | 2.3       |
| 2.4          | 0.89                   | 2.4       |
| 2.5          | 0.88                   | 2.5       |
| 2.6          | 0.87                   | 2.6       |
| 2.7          | 0.86                   | 2.7       |
| 2.8          | 0.85                   | 2.8       |
| 2.9          | 0.84                   | 2.9       |
| 3.0          | 0.83                   | 3.0       |
| 3.1          | 0.82                   | 3.1       |
| 3.2          | 0.81                   | 3.2       |
| 3.3          | 0.80                   | 3.3       |
| 3.4          | 0.79                   | 3.4       |
| 3.5          | 0.78                   | 3.5       |
| 3.6          | 0.77                   | 3.6       |
| 3.7          | 0.76                   | 3.7       |
| 3.8          | 0.75                   | 3.8       |
| 3.9          | 0.74                   | 3.9       |
| 4.0          | 0.73                   | 4.0       |
| 4.1          | 0.72                   | 4.1       |
| 4.2          | 0.71                   | 4.2       |
| 4.3          | 0.70                   | 4.3       |
| 4.4          | 0.69                   | 4.4       |
| 4.5          | 0.68                   | 4.5       |
| 4.6          | 0.67                   | 4.6       |
| 4.7          | 0.66                   | 4.7       |
| 4.8          | 0.65                   | 4.8       |
| 4.9          | 0.64                   | 4.9       |
| 5.0          | 0.63                   | 5.0       |
| 5.1          | 0.62                   | 5.1       |
| 5.2          | 0.61                   | 5.2       |
| 5.3          | 0.60                   | 5.3       |
| 5.4          | 0.59                   | 5.4       |
| 5.5          | 0.58                   | 5.5       |
| 5.6          | 0.57                   | 5.6       |
| 5.7          | 0.56                   | 5.7       |
| 5.8          | 0.55                   | 5.8       |
| 5.9          | 0.54                   | 5.9       |
| 6.0          | 0.53                   | 6.0       |
| 6.1          | 0.52                   | 6.1       |
| 6.2          | 0.51                   | 6.2       |
| 6.3          | 0.50                   | 6.3       |
| 6.4          | 0.49                   | 6.4       |
| 6.5          | 0.48                   | 6.5       |
| 6.6          | 0.47                   | 6.6       |
| 6.7          | 0.46                   | 6.7       |
| 6.8          | 0.45                   | 6.8       |
| 6.9          | 0.44                   | 6.9       |
| 7.0          | 0.43                   | 7.0       |
| 7.1          | 0.42                   | 7.1       |
| 7.2          | 0.41                   | 7.2       |
| 7.3          | 0.40                   | 7.3       |
| 7.4          | 0.39                   | 7.4       |
| 7.5          | 0.38                   | 7.5       |
| 7.6          | 0.37                   | 7.6       |
| 7.7          | 0.36                   | 7.7       |
| 7.8          | 0.35                   | 7.8       |
| 7.9          | 0.34                   | 7.9       |
| 8.0          | 0.33                   | 8.0       |
| 8.1          | 0.32                   | 8.1       |
| 8.2          | 0.31                   | 8.2       |
| 8.3          | 0.30                   | 8.3       |
| 8.4          | 0.29                   | 8.4       |
| 8.5          | 0.28                   | 8.5       |
| 8.6          | 0.27                   | 8.6       |
| 8.7          | 0.26                   | 8.7       |
| 8.8          | 0.25                   | 8.8       |
| 8.9          | 0.24                   | 8.9       |
| 9.0          | 0.23                   | 9.0       |
| 9.1          | 0.22                   | 9.1       |
| 9.2          | 0.21                   | 9.2       |
| 9.3          | 0.20                   | 9.3       |
| 9.4          | 0.19                   | 9.4       |
| 9.5          | 0.18                   | 9.5       |
| 9.6          | 0.17                   | 9.6       |
| 9.7          | 0.16                   | 9.7       |
| 9.8          | 0.15                   | 9.8       |
| 9.9          | 0.14                   | 9.9       |
| 10.0        | 0.13                   | 10.0      |
Table 3. Interpretation from line 9.

| Number | Depth (km) | Contrast Density (gr/cm$^3$) | Density (gr/cm$^3$) | Interpretation |
|--------|------------|------------------------------|----------------------|----------------|
| 1      | 0 – 1      | 0                            | 2.44                 | Andesite       |
| 2      | 0.5 – 1.9  | -0.100                       | 2.34                 | Rhyolite       |
| 3      | 0.7 – 2.2  | -0.100                       | 2.34                 | Rhyolite       |
| 4      | 1.6 - 3    | -0.060                       | 2.38                 | Rhyolite       |
| 5      | 1.2 - 3    | 0.065                        | 2.505                | Andesite       |
| 6      | 1.2 - 3    | 0.100                        | 2.54                 | Andesite       |

Generally, the modelling results for each section confirmed that in the subsurface survey area has a different type of rock based on its density. Commonly, the subsurface layer is composed by andesite and rhyolite. Rhyolite layer has a density value lower than andesite density, it means that the rhyolite has a higher porosity than andesite. The geothermal reservoirs probably present in a low porosity rock that is in rhyolite structure in the depth in variety of depth between 1.5 – 3 km.

4. Conclusion
The CSAMT and Gravity methods applied at Tangkuban Parahu area was successful to locate an anomalously low resistivity zone that may indicate the existing of a potential geothermal reservoir. From the CSAMT interpretation, results there are three layers of subsurface in the measurement area, that is the first layer a resistivity of 30 – 150 ohm-m and thickness of 800 to 1000 m, second layer has an extremely low resistivity of 3 – 15 ohm.m with 1000 – 1500 m thick. Finally, the basement (third) layer that is relatively more resistive than the second layer with resistivity of 30 – 100 ohm-m.

From the gravity interpretation results geological structure beneath the surface of Mount Tangkuban Parahu consist of andesite with density value of 2.4 – 2.6 gr/cm$^3$ and rhyolite with density value of 2.3 – 2.4 gr/cm$^3$. From the interpretation result, the geothermal reservoir is estimated to be in rhyolite.

From the model of CSAMT and Gravity in Line-3, both models show that there is anomaly distributed in the Northeast area. This may consider as hydrothermal alteration zone in geothermal reservoir structure. From Line-8 both models show anomaly in the Southeast area. And from Line-9, both model show the low resistivity in the depth around 800 – 1000 meters.

Furthermore, if it is possible in the future, the area can be exploited to produce a geothermal energy for generating the electricity after doing several geophysical, geological and geochemical exploration. For the reason, the geothermal energy is one of the energy alternatives in Indonesia.

Acknowledgments
Authors wishing to acknowledge to Program Penelitian, Pengabdian kepada Masyarakat, dan Inovasi (P3MI) ITB for funding of the research in the year of 2017.

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