2D Interpretation Of Controlled Source Audio Magnetotelluric (CSAMT) Data Integrated With Borehole Data In Kamojang Geothermal Field West Java, Indonesia

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Abstract. CSAMT is the one of electromagnetic method which uses unnatural source grounded dipole with the range of frequency between 0.1Hz-10 kHz. In order to qualify the response measured is plan wave, then the corrected source effect. The objective of this study was to obtain that have been corrected for source to have the same characteristic as MT data. CSAMT data that has been corrected, subsequently inverted to get the exact model and validated to well log data in the form of temperature data. After interpretation found that the some of the line measurement at geothermal field Kamojang has two layers. There are seven line, line-1 until line-7, line-2 until line-7 have the characteristic of geothermal, the first layer has a resistivity of 3-15 Ω.m and the average of thickness of 400-1500 meters. The second layer has a resistivity value of 20-300 Ω.m that is more resistive than the first layer, except for line 1, there is no low resistivity in the first layer. The first layer is a layer of clay, identified with resistivity values ranging from 2.5 - 15 Ω.m with 900-1400m thickness with temperature data on KMJ-12 range 180-200°C, and the next layer is more resistive layer than the second layer is 18 Ω.m -100 Ω.m with temperature data at KMJ-53 at a depth of 710 meters is 240°C.

Keywords: : CSAMT method, Resistivity, Temperature.

1. Introduction
A Controlled source audio frequency magnetotelluric (CSAMT) measurement, in the operating frequency range of 0.25 to 8192 Hz, the location transmitter was about 3-5 km in the southwest from the survey area, the sounding sites were distributed irregularly and the distance between each of them varied from 200-500 m [1]. The purpose of the measurements is to demonstrate the capability of the CSAMT method used for a geothermal exploration by locating an anomalous low resistivity zone associated with the existence of geothermal reservoir and validated with the temperature data. For information about the temperature and minerals obtained from the results of research [2].

The Kamojang geothermal field which is located in West Java. The CSAMT survey area is geographically between 07° 10’30” – 07° 07’30” South latitude and 107° 45’ 30” East longitude.
Kamojang is the geothermal that placed in Garut, West Java and operating since 1983, it has been producing a sufficient steam of the vapor dominated resources for generating electricity with the total installed capacity of about 200 MW [3].

Kamojang geothermal field is located in Garut approximately 42 km south-east of Bandung city. This area is vapor dominated system and high temperature around 235°-250°C. This heat interacts with fluids forming hydrothermal alteration rock that serves as a cap rock and reservoir in the Kamojang geothermal system. This area was first discovered by Dutch in 1920 and the early exploration in 1973 with the cooperation between the government of Indonesian and New Zealand [4]. After 10 years of exploration this field produces in 1983 to producing 140 MWe and in 1997 expanded to 220 MWe [5]. CSAMT method has successfully applied for ground water exploration in a suburban Beijing [11], also successfully mapped the results of uranium exploration [6]. CSAMT method has successfully mapped the distribution of resistivity in the geothermal field Takigami in Kyushu [7], CSAMT method was used to map brine contamimation in the vicinity of the Prue Sand Unit [8]. CSAMT method was successfully for uranium exploration, the data show a good correlation to geology [9]. Controlled source audio-frequency magnetotellurics (CSAMT) is a frequency-domain electromagnetic sounding technique which uses a fixed grounded dipole or horizontal loop as an artificial signal source.

The cooler upper zones are characterized by alteration of electrical conductive layer that is formed at temperatures above 70°C. At higher temperatures, illite of less conductive layer becomes interlayered with smectite. The proportion of illite increases with the temperature, forming about 70% of the mixed-layer clay at 180 °C. Above this temperature, the smectite content continued to decrease and pure illite commonly appears at greater than 220 °C [10].

![Figure 1. A generalized geothermal system](image)

2. CSAMT Theory

The CSAMT is electromagnetic method which use unnatural source with the range of frequency is 0.1Hz-10kHz, unnatural source electromagnetic is the electric current which approach 10A that injection to the earth. Basic theoretical principle for CSAMT theory can be described in terms of Maxwell’s equations.

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

(1)

\[ \nabla \times \vec{H} = \vec{J} - \frac{\partial \vec{D}}{\partial t} \]

(2)

\[ \nabla \cdot \vec{D} = \rho \]

(3)

\[ \nabla \cdot \vec{B} = 0 \]

(4)

With the assumption of electromagnetic field behavior within the conducting half space in a cylindrical coordinat system and used modified of Bessel function:

\[ E_z = \frac{\text{Main d}}{2\pi \sigma r} \left[ \frac{1}{r} J_1 \left( \frac{i \sigma r}{2} \right) + \frac{i \sigma r}{2} I_1 \left( \frac{i \sigma r}{2} \right) k_z \left( \frac{i \sigma r}{2} \right) - I_1 \left( \frac{i \sigma r}{2} \right) k_z \left( \frac{i \sigma r}{2} \right) \right] \]

(5)

\[ H_z = \frac{\text{Main d}}{2\pi r} \left[ 3I_1 \left( \frac{i \sigma r}{2} \right) k_z \left( \frac{i \sigma r}{2} \right) + \frac{i \sigma r}{2} J_1 \left( \frac{i \sigma r}{2} \right) k_z \left( \frac{i \sigma r}{2} \right) - J_1 \left( \frac{i \sigma r}{2} \right) k_z \left( \frac{i \sigma r}{2} \right) \right] \]

(6)
Where $dl$ is the dipole length, $r$ is the source-sounding distance, $I_m$ and $K_m$ are modified Bessel function of the $m$-th order. Far from dipole source, equations (5) and (6) approach the following limits, with quasi static assumption:

$$\frac{E_{\phi}}{\pi \sigma r^2} = \frac{I_m(\frac{dl \sin \phi}{\mu_0 \sigma r})}{r^3}$$

$$\frac{H_z}{\pi \sigma r} = \frac{K_m(\frac{dl \sin \phi}{\mu_0 \sigma r})}{r^3}e^{i\frac{r}{\mu_0 \sigma}}$$

As shown in equations (7) and (8) the horizontal fields in the far field zone all decay as $1/r^3$, the far field apparent resistivity can be determined by measuring the perpendicular E and H, that is [12]:

$$\rho_{\text{app}} = \frac{1}{\mu_0 |H_z|}$$

Because of the need to minimize the transmitter-receiver separation for maximum signal, the far filed zone is restricted by this situation, therefore, most CSAMT data sets will contain some near-field and transition zone data. To overcome the source effect problem, a correction technique to CSAMT data should be applied to obtain apparent resistivity value equivalent to the far field situation. In this paper, a technique to correct near-field CSAMT apparent resistivity proposed by Yamashita et al [10]. The technique suggest that the plane wave apparent resistivity calculated by near field equation for the lower frequency and the apparent resistivity calculated by Cagniard equation for the high frequency.

The 2D inversion has been used for many years to interpret automatically CSAMT data. This technique makes the interpretation more objective and less time consuming then the trial and error approach but it does not yield a unique solution. Nevertheless, a common approach to fitting a 2D CSAMT data set is construct a cross-section of the area based on prior geological knowledge and the model parameterization to solve for the conductivities by least-square inversion. A 2D inversion scheme using the non-linier conjugate gradients (NLCG) algorithm proposed by Rodi and Mackie was applied to the corrected CSAMT data of transverse magnetic mode. The NLCG scheme minimizes an objective function that penalized data residuals and the second spatial derivatives of the resistivity.

Tikhonov’s method defines a regularized solution of the inverse problem to the model that minimize to object function:

$$\nu(m) = \frac{1}{2} \|d - F(m)\|^2 + \lambda \|L(m - m_0)\|^2$$

Where $d$ is observed data vector, $m$ is an unknown model vector, $m_0$ is a priori model, $F$ is a forward modeling operator, $V$ is an error covariance matrix, $L$ is a linier operator and $\lambda$ is a regularization parameter. Each datum $d_i$ is log amplitude or phase of transverse electric (TE) or transverse magnetic (TM) mode of complex apparent resistivity at a particular station and frequency. The model vector is also log resistivity as a function of position $m(x) = \log(\rho(x))$. The Laplacian operator can be written as follow:

$$\Delta(m - m_0) = \int \left(\frac{\partial^2 (m(x) - m_0(x))}{\partial x^2}\right)dx$$

The model sequence is given by:

$$\nu(m + a, h) = \min \nu(m + ah)$$

$$m_{j+1} = m_j + ah_j$$

$$h_{j+1} = -C_j g_{j+1} + \beta_j h_j$$

Where $aj$ is a size step, $hj$ is a search direction, $Cj$ is a preconditioner, $g_t$ is a gradient of objective function and $\beta_j$ is a scalar calculated as:

$$\beta_j = \frac{g_{j+1}^T C_j g_{j+1}}{g_j^T C_j g_j}$$
3. CSAMT Data Interpretation

In this paper, a two-dimensional (2D) inversion technique based on a non linear conjugate gradient method using finite element discretization was applied to invert the corrected CSAMT data.

The measuring of CSAMT method can described in the figure 2. There are seven lines (line 1-line 7) and there are 60 soundings. After the correction effect source is done to all sounding source, then we do the inversion process.

4. Correlation of 2-D Inversion Result with well Log Data

To confirm the 2-D CSAMT inversion results, the temperature data from wells KMJ-7, KMJ-10, KMJ-11, KMJ-59, KMJ-12, KMJ-52, KMJ-53 and KMJ CHR-1. That wells are spread in lines, KMJ-7 in line-4, KMJ-10 in line-2, KMJ-59 in line 4, KMJ-12 in line-7, KMJ-53 in line-6 and KMJ CHR-1 in line-2. The picture below is the resistivity section and the temperature values.

According to the result obtained through the 2-D inversion result of CSAMT data in TM mode, the 2D resistivity mode section for each profile can be seen from the figure 3-9. The color in each area shows the resistivity value, the blue color indicates a high resistivity value, NE direction in Line 1 it has high resistivity and NE direction. In line 2 there are two wells, KMJ CHR-1 and KMJ-10, in KMJ
CHR-1 in the depth 1500-1000 m asl the temperature is ±100°C with the mineral is Crystobalite-Montmorillonite with resistivity’s profile of 2D is 2.5-151 Ω.m.

In the depth 1000-500 m asl the temperature is 100-200°C with illite-montmorillonite the mineral is formed and the value of resistivity is around 2.5-22.5 Ω.m. On the sea level until 500m asl the temperature is 245-250 °C with the mineral is formed is Chlorite epidote with the resistivity value above 15-151 Ω.m.

Figure 5 shows the inversion result in line 3 and figure 6 is 2D inversion section for line 4, there is low resistivity value in SW direction of line 3 with a thickness 1500 m below the surface. In line 4 there is KMJ-7 with the temperature 220° in the depth 433 meter and the resistivity value is 10-15 Ω.m with the mineral’s formed is laumontite. In the depth 96 meter the mineral’s formed is wairakite with the temperature is 140°C and the value of resistivity is 2.5-10 Ω.m.

The line 5 has a layer with a thickness of 1000 to 1500 m below the surface with resistivity value is 2.5-10 Ω.m and the line 6 there is KMJ-53 in the depth 710m below ground level with the temperature 240oC with the resistivity value between 5-15 Ω.m, the content of mineral is wairakite.
In line 7 there is KMJ-12 in the depth 1000m below ground level with the temperature 180-200°C with the resistivity value is 3-15 Ω.m, the content of mineral is wairakite.

5. Conclusions

Based on the results of measurements of CSAMT in geothermal field, Kamojang. The CSAMT method applied was successful to locate an anomalously low resistivity zone that indicates a potential geothermal reservoir. Generally, the subsurface resistivity structures in Kamojang geothermal field are composed mainly by two types of resistivity feature obtained from 2D inversion results of CSAMT data. Generally, the Kamojang area is composed mainly of two layers of resistivity structure. Line 2 until line 7 has the characteristic of geothermal, the first layer has a resistivity of 3-15 Ω.m and the average of thickness of 400 -1500 meters. The second layer has a resistivity value of 20-300 Ω.m that is more resistive than the first layer, except for line 1, there is no low resistivity in the first layer. The electromagnetic exploration methods are more effective to detect a low resistivity zone on the vertical direction correlating with the existing alteration zone.

6. References

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