Synthetic Modeling of A Geothermal System Using Audio-magnetotelluric (AMT) and Magnetotelluric (MT)

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Abstract. Indonesia has 40% of the world's potential geothermal resources with estimated capacity of 28,910 MW. Generally, the characteristic of the geothermal system in Indonesia is liquid-dominated systems, which driven by volcanic activities. In geothermal exploration, electromagnetic methods are used to map structures that could host potential reservoirs and source rocks. We want to know the responses of a geothermal system using synthetic data of Audio-magnetotelluric (AMT) and Magnetotelluric (MT). Due to frequency range, AMT and MT data can resolve the shallow and deeper structure, respectively. 1-D models have been performed using AMT and MT data. The results indicate that AMT and MT data give detailed conductivity distribution of geothermal structure.
Keywords: *magnetotelluric, audio-magnetotelluric, geothermal system, resistivity*

1. Introduction
Indonesia has 40% of the world's potential geothermal resources. There is 28,910 MW electricity that can be generated from geothermal [1]. Recently, only 1,343.5 MW geothermal power plant capacity is used.

Geothermal systems are indicated by the presence of heat source, reservoir, and a cap rock [2]. Mostly, geothermal systems in Indonesia are the result of volcano activity. The subduction of Indo-Australian plate – southern part of Indonesia- and Eurasian plate in the northwest is the main cause of volcanoes. The volcanoes lie along Indonesia region, from Sumatera Island in the west to Papua Island in the east.

There are several differences between the geothermal system between Sumatera and Java - including Nusa Tenggara and Sulawesi [3]. In Sumatera island, the geothermal systems relate with Andesitic-Rhyolitic volcanoes with its viscous and acid magma. The geothermal systems are controlled by a regional fault within Sumatera fault. The reservoir is on sediment rocks and can be discovered in the shallow zone. Whereas, the reservoir of geothermal systems in Java, Nusa Tenggara, and Sulawesi are in the deep zone. The systems are associated with andesitic-basaltic volcanism, where the magma is less viscous.

2. Method

2.1 Magnetotelluric theory

Magnetotelluric (MT) method measures natural electromagnetic field, which is used to investigate the electrical conductivity structure of the Earth [4]. The measurement on the surface is carried out to determine the resistivity of subsurface by investigating electrical and magnetic field. Basically, there is no significant difference between MT and AMT. It just depends on measured frequency.

The increased reception band of AMT method allows us to measure resistivity and improve the model in the shallow zone. Meanwhile, MT records frequency in range 0.001 Hz - 10 kHz that can be used to detect geological structures deeper than about 1,000 meters, where target depths are typically in the range of 1,000-3,000 meters.

High frequency of electromagnetic only gives a shallow depth of penetration, because of energy absorption approximately 1/e or ~37% from amplitude value on the surface [5]. This phenomenon is called skin depth (δ). Propagating of electromagnetics wave in the earth is diffusion event rather than wave propagation itself.

$$\delta = 503 \left(\frac{\rho}{f}\right)^{1/2} \text{ (meter)} \qquad (1)$$

Where, ρ is resistivity and f is frequency.

2.2 Apparent resistivity and phase

Generally, 1-D MT responses are expressed as apparent resistivity (ρ_a) and phase (ϕ) [6]. Those can be calculated using following equation, where Z_1 is impedance on the earth surface,

$$\rho_a = \frac{1}{\omega\mu_0} |Z_1|^2 \qquad (2)$$

$$\phi = \tan^{-1}\left(\frac{\text{Im } Z_1}{\text{Re } Z_1}\right) \qquad (3)$$

3. Modeling

Modeling and data processing were accomplished in the Geoelectric and Electromagnetic Laboratory, Department of Geophysical Engineering, Institut Teknologi Bandung. We used synthetic data to make geothermal system model.

3.1 Conceptual model

The conceptual model contains geological and geophysical profile about geothermal system in Indonesia. There are five layers i.e. overburden, clay cap, reservoir, bedrock, and heat source. The overburden layer has various in depth from 500-800 m, and the resistivity is 70 Ωm.

The clay cap lies under overburden layer between 700-1000 m depth. The clay cap has the lowest resistivity 8 Ωm. After that, the following layers are the reservoir, bedrock, and heat source with each depth is 1000-2200 m, 2200-2500 m, and 3100-4000 m. The resistivity is 60 Ωm, 250 Ωm, and 850 Ωm.
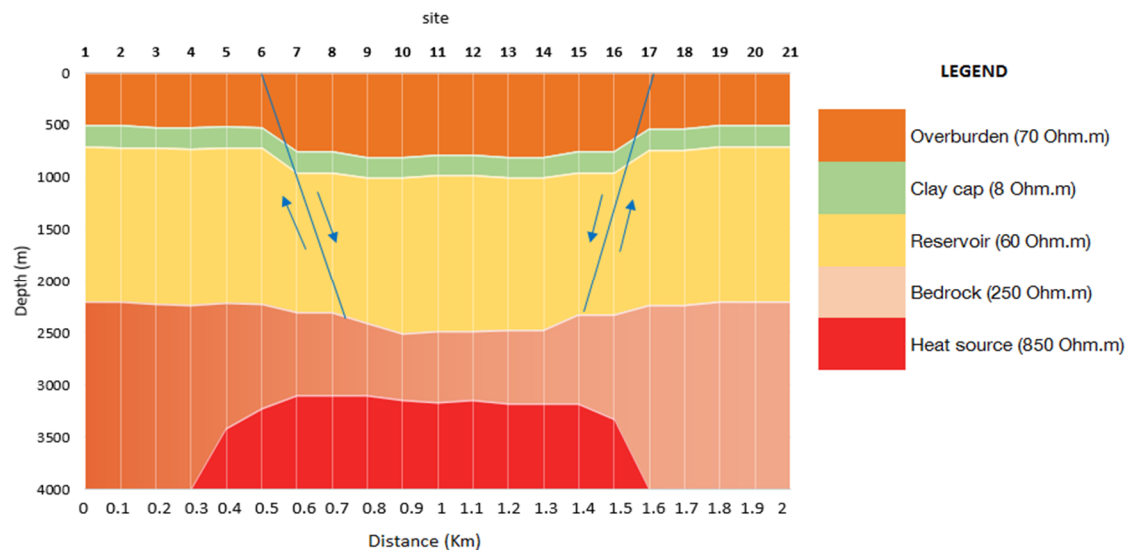
Fig. 1. A Conceptual model of the geothermal system in Indonesia with five layers, i.e. overburden, clay cap, reservoir, bedrock, and heat source. Each layer has resistivity value. The total depth is 4000 m. (Modified from [7])

3.2 Data processing
We obtained 21 synthetic data points from the conceptual model (see Fig. 1). Distance from a point to point is 100 meters. So, the total distance to be modeled is 2 km. We also need to input frequency range for each method, 0.001-1000 Hz for MT and 0.1 Hz-10 kHz for AMT. In the inversion processing, we used Levenberg-Marquardt algorithm.

In this paper, the model will be presented only in Site 1, Site 6, Site 10, and Site 18. In the Fig.2 shows the 1-D apparent resistivity models. The green line is resistivity model based on original information from resistivity value of forward modeling in each layer. The red line and blue line are the result of inversion of MT and AMT, respectively.
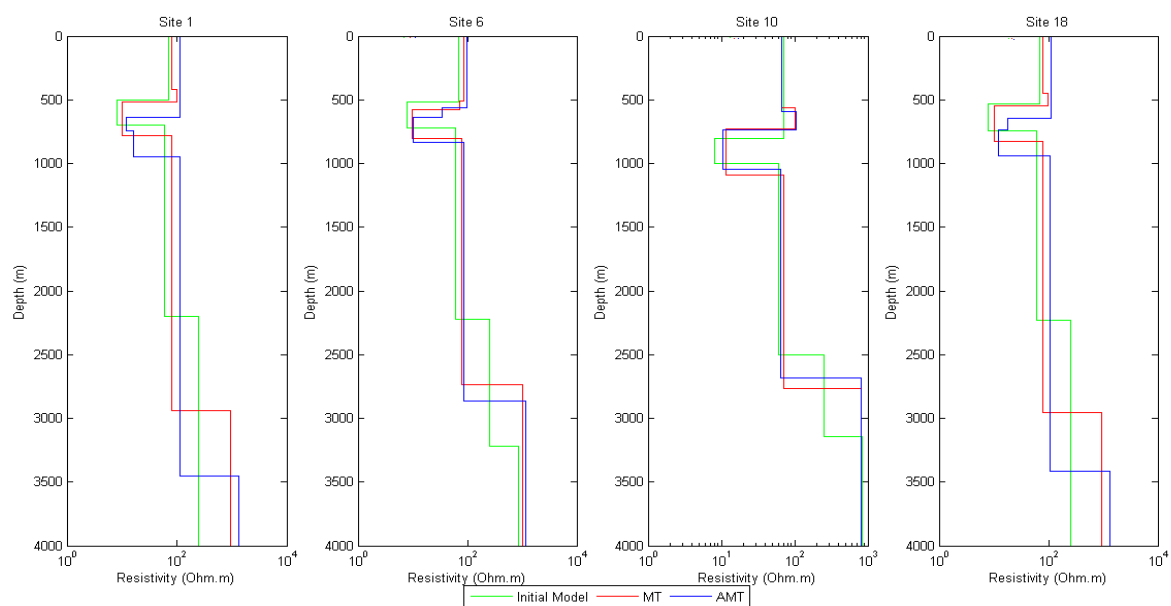

Fig. 2 1-D apparent resistivity models of MT and AMT in the Site-1, Site-6, Site-10, and Site-18.

4. Discussion

The 1-D resistivity models of some sites are plotted as in Fig.2. In this paper, we only discuss 1-D resistivity model of Site-1, Site-6, Site-10, and Site-18.

The curves (Fig. 3) can show the responses of MT and AMT data in Site-1 and Site-6. Responses for Site-10, and Site-18 in the (Fig.4). In the curve of Site-1, the graph increases when in the frequency 3-30 Hz. The curve between frequency and phase also increases at the same frequency. It shows phase change from less than 45 degrees become more than 45 degrees. It indicates that the electromagnetic wave passed through the conductive layer. From (Fig.2) the conductive layer lies between 500-1000 m depth.

Other curves for Site-6, Site-10, and Site-18 also give a similar result, that the conductive layer can be detected. The conductive layer is clay cap, and the reservoir lies underneath the clay cap, which becomes the main target of geothermal exploration.
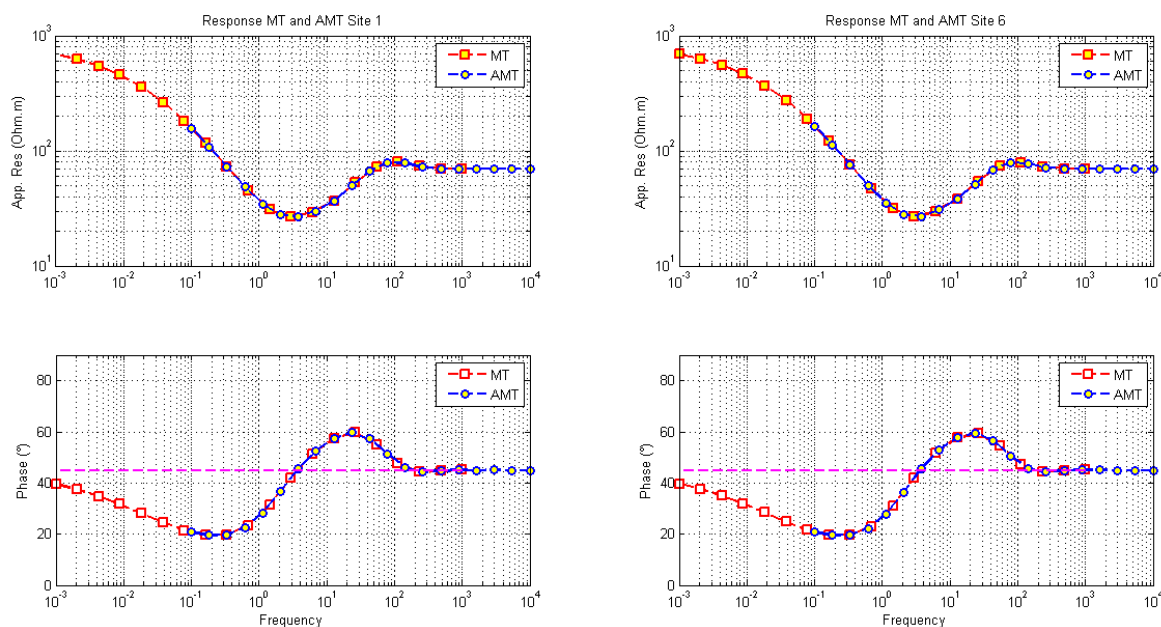
Fig.3 Response MT and AMT in Site-1 and Site-6. The curve between frequency and apparent resistivity (top) and curve between frequency and phase (bottom).
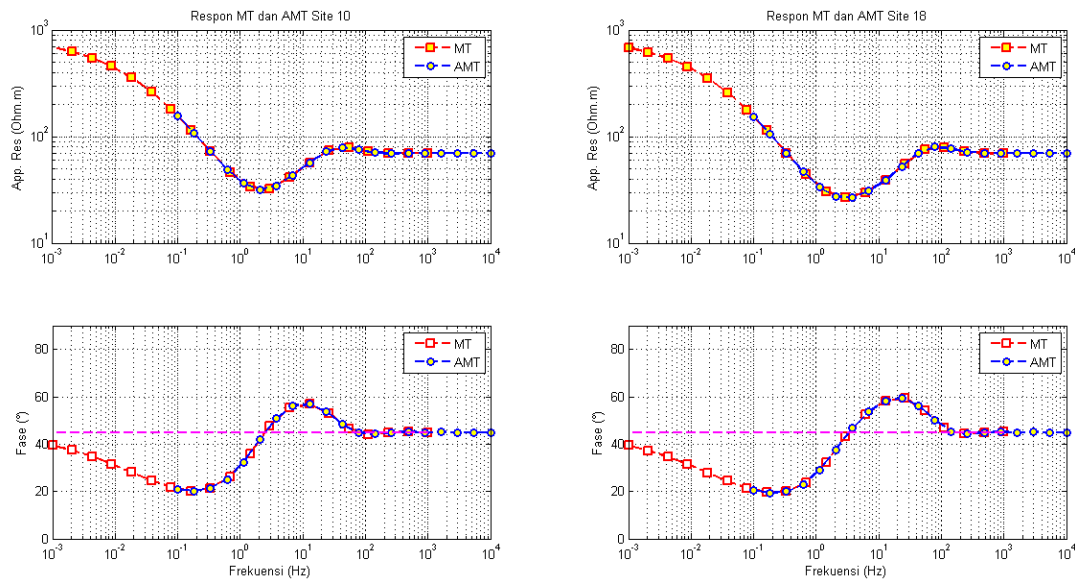
Fig.4 Response MT and AMT in Site-10, and Site-18. The curve between frequency and apparent resistivity (top) and curve between frequency and phase (bottom).

5. Conclusion

The result indicates that synthetic model of AMT and MT give detailed conductivity distribution of geothermal structure, from the surface to basement. AMT data can give an image of the structure in the shallow depth. While, from MT data we know better the structure in the deep zone where the heat source exists.

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