Simulation of 3-D Effect in Magnetotelluric (MT) Data and Its Influence on Inversion Modeling

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ABSTRACT

Magnetotelluric (MT) data can be affected by 3-D effect especially in geothermal area which has a complex geological condition. This phenomena is caused by complex lateral variation of subsurface resistivity structure. It has been learned by simulation using 3-D MT forward modeling. Several resistivity model were built as representation of 1-D, 2-D, and 3-D earth model. In 1-D earth model, resistivity varies only with depth. In case of 2-D earth, resistivity changes with depth and in one horizontal direction. For 3-D earth model, resistivity is varies in all direction. MT response, represented by apparent resistivity & phase curve in frequency domain was then calculated & analyzed in every station for each model. The MT response from each model clearly shows the effect to the MT data. Moreover, the research was continued to learn the influence of 3-D effect in MT inversion modeling. All of MT inversion algorithm was developed under certain assumption. Dimensionality of the model is the most important assumption that must be considered. 1-D, 2-D, and 3-D inversion were then applied to all MT data which is derived from MT forward modeling. The inversion result show that 3-D approach give more reliable model and can be overcome the 3-D effect. Accordingly, MT data in complex geological structure like in geothermal area should be approached by 3-D inversion.

INTRODUCTION

Magnetotelluric (MT) method is a passive electromagnetic method which is commonly used to delineate the subsurface resistivity structure especially in geothermal area. Natural EM variation is recorded for several hours for each station on the surface. Subsurface resistivity variation could be obtained by applying several steps of data processing and various schemes inversion modeling.

In the real earth, the subsurface resistivity structure might be very complex. The rock resistivity value varies in all direction, both vertical and lateral. Ussher et al (2000) have reviewed the factors affecting resistivity in geothermal systems such as alteration minerals, fluid content, and temperature. The lateral resistivity variation affected the MT data is called a 3-D effect. In an ideal 1-D earth structure, the MT Curve for both TE & TM mode give a similiar response, but in the real earth structure TE & TM mode are different. The 3-D effect produces different response of TE & TM mode due to the presence of resistivity variation in lateral direction.

This paper discusses about the simulation of 3-D effect in MT data using 3-D MT forward modeling. Several resistivity model were built as representation of 1-D, 2-D, and 3-D earth model. MT response, represented by apparent resistivity & phase curve in frequency domain was then calculated & analyzed in every station for each model. The MT response from each model clearly shows the effect to the MT data. The research was also continued by analyzing the influence of 3-D effect in MT inversion modeling of 1-D, 2-D, and 3-D. The similar comparison of those inversion method have been studied by Siripunvaraporn et al (2005), Cumming & Mackie (2010), Lestari et al (2016), and Daud (2016) using synthetic and real MT data.

MT CONCEPT

MT method employs electromagnetic wave variation to obtain subsurface resistivity distinction. The electromagnetic wave consist of E and H field. E field varies along lateral direction and H field varies along vertical and lateral direction. H field come from the earth atmosphere and propagate through the earth layer. Because of the propagation, E field emerges from the earth layer.

The ratio of the horizontal electric field to the orthogonal horizontal magnetic field (termed the EM impedance, Z, equation (1)), measured at a number of frequencies, gives Earth resistivity (called apparent resistivity) as a function of frequency or period, resulting in a form of depth sounding.

$$\boldsymbol{Z_{xy}} = \frac{\boldsymbol{E_x}}{H_y} \tag{1}$$

Apparent Resistivity is an average resistivity for the volume of Earth sounded by a particular MT sounding period. Apparent resistivity is related to impedance via Equation (2). For an homogeneous Earth the apparent resistivity represents the actual resistivity, whereas for a multi-dimensional Earth, the apparent resistivity is the average resistivity represented by an equivalent uniform half-space. (Simpson & Bahr, 2005)

$$\boldsymbol{\rho_{xy}} = \frac{\boldsymbol{1}}{\boldsymbol{\omega\mu}} \left|\frac{\boldsymbol{E_x}}{\boldsymbol{H_y}}\right| \tag{2}$$

Where ω Is angular frequency ($\omega = 2\pi f$) and μ is magnetic permeability. In studies of the Earth, μ is usually assigned the free-space value ($\mu_0 = 4\pi \, x \, 10^{-7} \, H \, m^{-1}$)

The phase difference between the electric and magnetic field can be calculated by using equation (3).

$$\emptyset_{xy} = \boldsymbol{tan^{-1}} \, (\boldsymbol{Z_{xy}}) \tag{3}$$

Lateral resistivity variation can affect the MT data even though the boundary located far away from MT station. Resistivity anomaly can affect from 2-3 times distance of sounding penetration (Simpson & Bahr, 2005). Lateral resistivity variations disturb the sounding volume of the ideal layered model. Figure 1 shows the effect of conductive anomaly to a 30 km apart MT station.

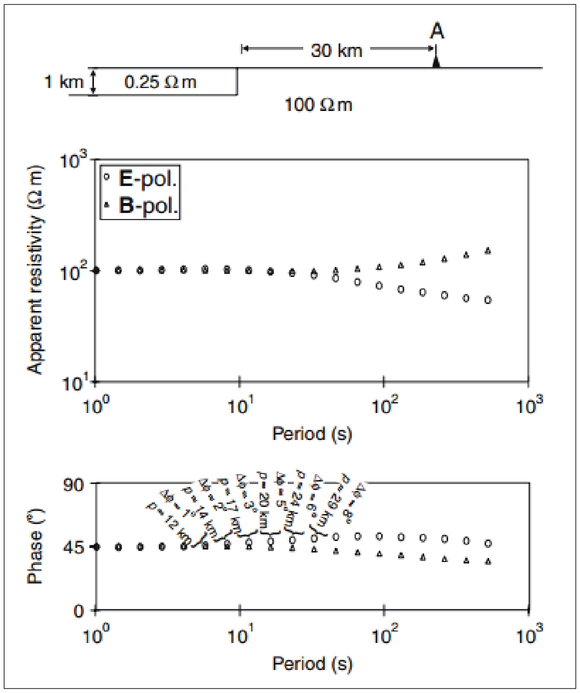

Figure 1. 3-D effect on MT data causing by lateral variation on 30 km distance from MT station. (Simpson & Bahr, 2015)

Impedance Tensor

The relationship between **E** and **H** are represented by tensor impedance matrix. Those matrix is written as:

$$Z = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \quad (4)$$

The matrix component values are depend on the dimensionality of resistivity model.

1-D Model

1-D model is assumed that the resistivity only varies in vertical direction, there is no lateral variation. Both **E** in x and y direction have same amplitude, but have inverted value because of their direction. The Z_{xy} and Z_{yz} have same amplitude but inverted value. So, the impedance matrix can be written as:

$$Z = \begin{bmatrix} 0 & Z \\ -Z & 0 \end{bmatrix} \quad (5)$$

2-D Model

2-D model is assumed that the resistivity varies vertically and laterally in a direction. The other lateral direction has homogenous resistivity. The homogenous area commonly called as geoelectric strike or strike.

The resistivity distribution affect the electric component propagation. It will be disturbed when propagates along area with resistivity contrast, whether electric field along homogenous area is not disturbed. Those two component have different value, so Zxy and Zyx have different value too. The impedance matrix than can be written as:

$$Z = \begin{bmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{bmatrix} \quad (6)$$

There are two independent modes in MT method that is TE mode (Transfers Electric) and TM (Transfers Magnetic) mode. TE mode measures electric component parallel to geolectric strike, whether TM mode measures magnetic component parallel to geolectric strike. Those configuration can bee seen at figure 2.

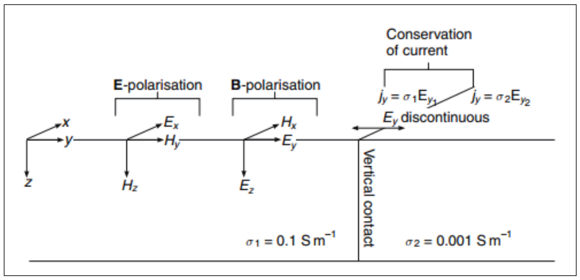

Figure 2. TE mode & TM mode. (Simpson & Bahr, 2015)

3-D Model

3-D model assume that resistivity values varies in all direction, vertically and laterally. Electric field is locally polarized and induced magnetic field which have direction not 90^0 to the main electric field (Naidu, 2012). This condition alter the correlation between electric component and magnetic component, and can be written as:

$$E_x = aH_x + bH_y \quad (7)$$

Where a and b are coupling coefficients which depend to position, coordinate direction, period, geometry, and the electric properties of lateral inhomogenity. The impedance matrix then written as :

$$Z = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \quad (8)$$

All the impedance tensor components have value. Z_{xx} and Z_{yy} can be called as impedance which are caused by 3-D model.

3-D EFFECT SIMULATION

Several synthetic models were built for performing a simulation of 3-D effect in MT data. The models are representation of 1-D, 2-D, and 3-D earth model. The synthetic model is consist of several blocks with certain resistivity value in a 3-D mesh grid. The mesh grid and the forward parameter used in the modeling is described in Table 1.

Table 1. Mesh Grid & Forward Parameter

MESH GRID PARAMETER	
Block Size	250 x 250 x 100 m
Out of Grid / Padding Factor	5 / 1.5
Number of Block	43 x 43 x 19
FORWARD PARAMETER	
Number of Station	64 / 1000 m
Freq. Range / Point Per Decade	1000 – 0.01 Hz / 8

1-D Earth Model

1-D earth model could be represented as stratified layer model which have different resistivity value for each layer. A typical high-low-high resistivity structure usually observed in a geothermal area. The first high resisitivity layer related to the fresh rock in the near-surface which has resistivity value about 100-500 ohm-m. The second layer is a conductive layer which has 1 to 10 ohm-m due to the presence of clay alteration as a product of hydrothermal process. Below this layer the resistivity value is increase gradually from 10 to 100 ohm-m in the reservoir zone and will increase to more than 100 ohm-m when reaches the basement layer.

A model of 1-D earth layer was built as shown in figure 3. No lateral resistivity variation exist in the model. The resistivity value varies only in vertical direction. The model consist of five layers with resistivity value 100, 10, 50, 100, and 200 ohm-m respectively. 3-D forward modeling was then performed to calculate the MT response in 64 stations.

Figure 4 shows the 3-D forward modeling result of the 1-D earth model. The MT response that was generated from 3-D forward calculation give almost similar response for TE & TM mode. There is only small different response value of TE & TM because of the edge effect. The same resistivity structure below each MT station produce a similar response in each station.

1-D MT inversion was then performed to several MT data along a profile in the center of the model. For 1-D earth model, 1-D inversion approach seems clear enough to generate a model that similar with the original. The inversion result can be seen in Figure 5.

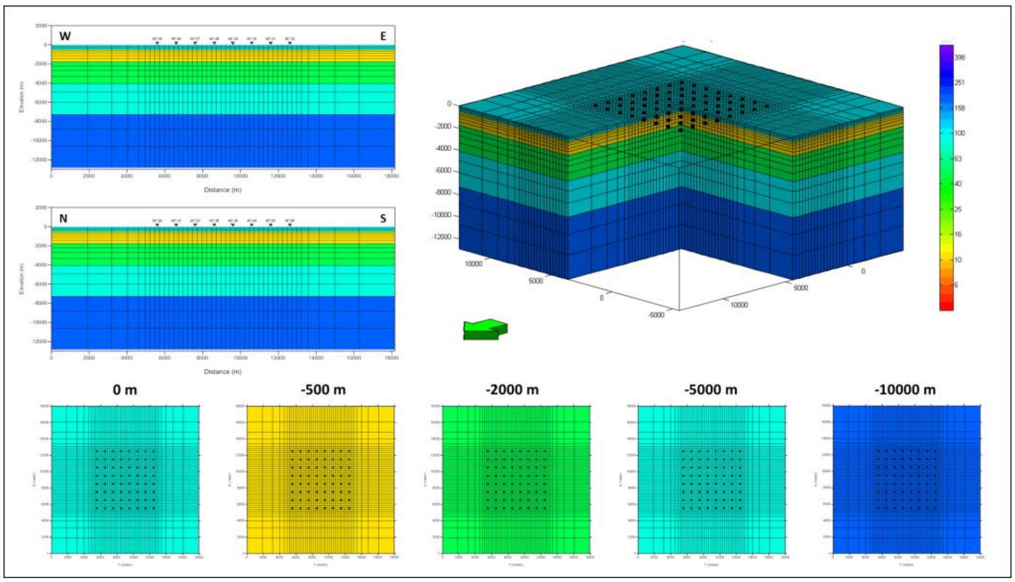

Figure 3. 1-D earth model.

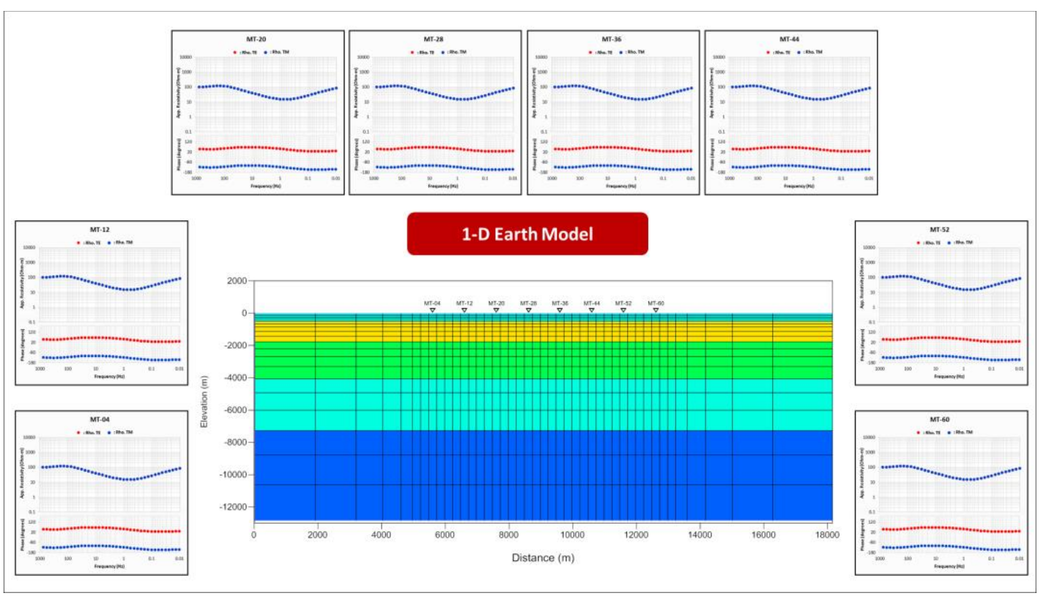

Figure 4. MT response of 1-D earth model derived from 3-D forward modeling.

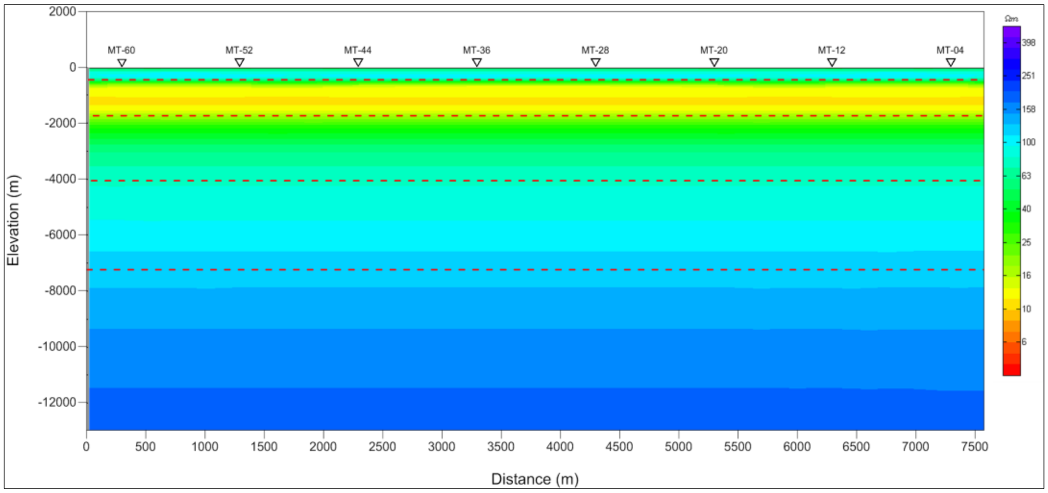

Figure 5. 1-D (TE/TM/Invariant) inversion result of 1-D earth model.

2-D Earth Model

The simulation was then continued using a 2-D Earth model. The model, as shown in figure 6, was constructed with additional resistive body (200 ohm-m) in the northern side. It generates lateral resistivity variation in the north-south direction. There is no change for vertical variation.

Similar to 1-D model, the 3-D forward calculation was then performed to get the MT response in each stations. The 3-D forward modeling result is shown in figure 7. It can be seen that the presence of lateral resistivity variation in the model affected the MT data represented by different response of TE & TM in each station and different response with MT data that was obtained from the 1-D model. The effect is influenced by the distance between station and boundary of the resistivity contrast.

The effect can be seen not only in the MT response but also the inversion result. 1-D & 2-D inversion was applied to this model. Due to the difference response of TE and TM, the 1-D inversion was then carried out for three different mode, TE, TM, and Invariant. The inversion results (figure 8) show that the 1-D inversion is not effective enough to recover the original model. The inversion model produced from 1-D inversion is disturbed when recovering the geometry and the resistivity value of the model anomaly especially in the bottom of conductive layer. Meanwhile, the 2-D inversion show a better result. For 2-D earth model, the 2-D inversion approach seems more appropriate to apply in 2-D MT data because it can produce more reliable result compare with 1-D inversion model. The geometry as well as the resistivity value of the original model can be observed clearly in the 2-D inversion model.

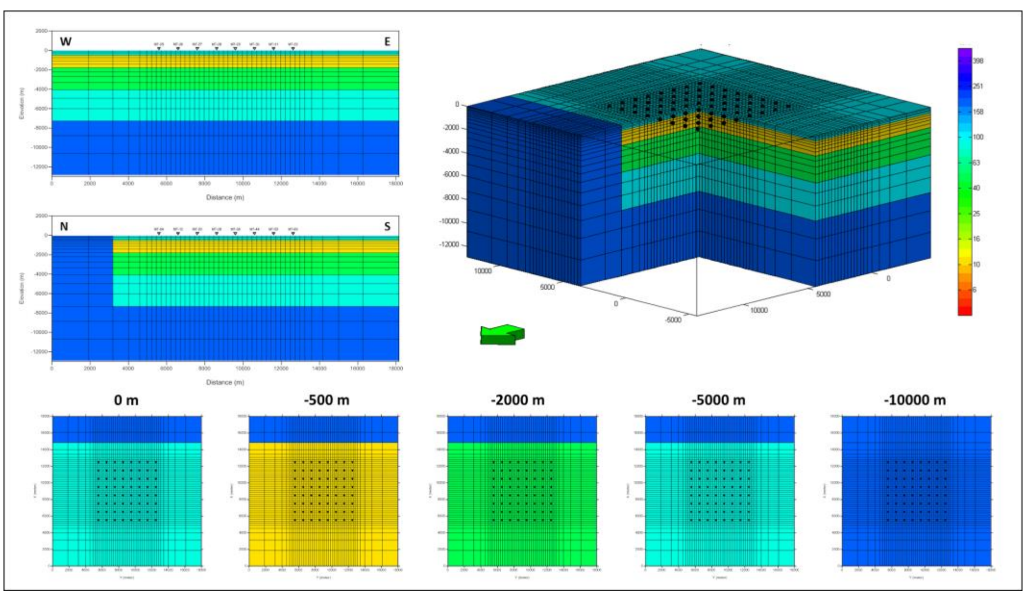

Figure 6. 2-D earth model.

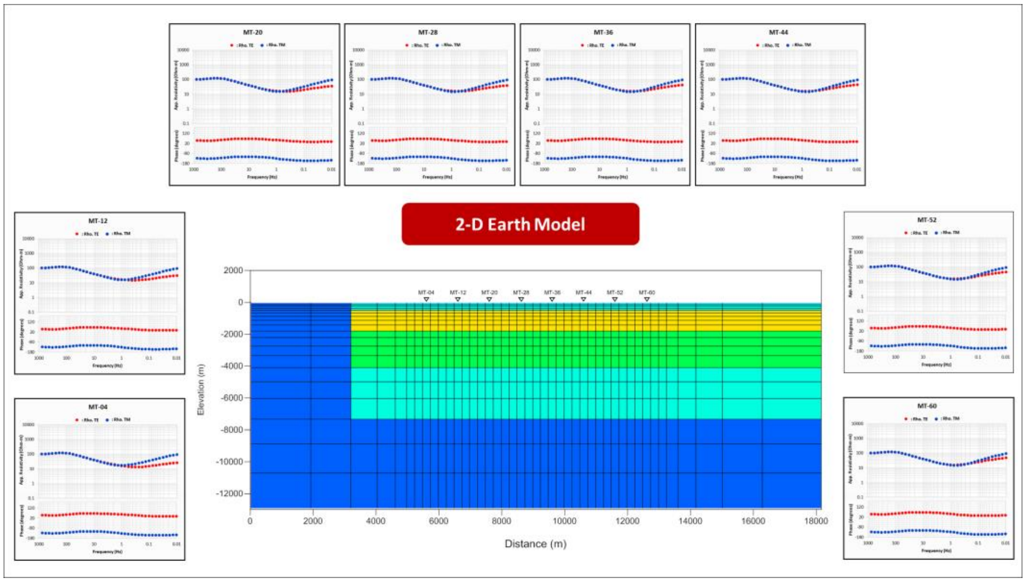

Figure 7. MT response of 2-D earth model derived from 3-D forward modeling.

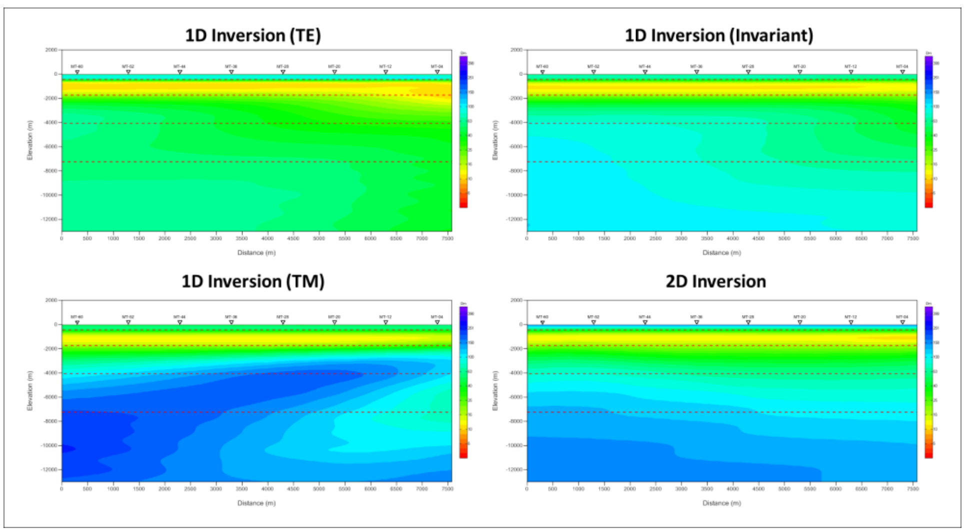

Figure 8. 1-D (TE/TM/Invariant) & 2-D inversion result of 2-D earth model.

3-D Earth Model

The 3-D earth model was constructed with a different scheme. In 2-D earth model the lateral variation was made by adding a resistive body (200 ohm-m) in the outer side of the interest area. For 3-D earth model, the resistive body (250 ohm-m) was added inside the interest area below several MT stations, see figure 9. Furthermore, 3-D forward and 1-D, 2-D, 3-D inversion modeling were applied to test the influence of 3-D effect. The forward calculation response of the model is shown in figure 10. It can be seen that the MT data along the profile was influenced by this effect. The effect was characterized by a different response of TE and TM in MT stations especially in the outside of the resistive body. Even the resistivity structure below the MT-04 and MT-12 is similar in 1-D, 2-D, and 3-D earth model but the response of the MT data is different for all model, see figure 12. It is caused by lateral resistivity variation in each model that affecting the MT data. It is then called as a 3-D effect. The comparison of the MT response can be seen in figure 6. Figure 11 shows the inversion result derived from 1-D, 2-D, and 3-D inversion modeling. It can be seen for the 3-D earth model that the 1-D and 2-D inversion approach seem not clear enough to reconstruct the original model through the inversion calculation. The geometry of the resistive body is poorly identified especially from 1-D TM and 2-D inversion result. The presence of conductive layer in the top of the resistive body could not also be defined clearly. The different result is shown by 3-D inversion result that produce good inversion model. The geometry of the resistive body as well as the presence of the conductive layer is well identified in the model. However, the resistivity value of the bottom part is not appropiate with the original model.

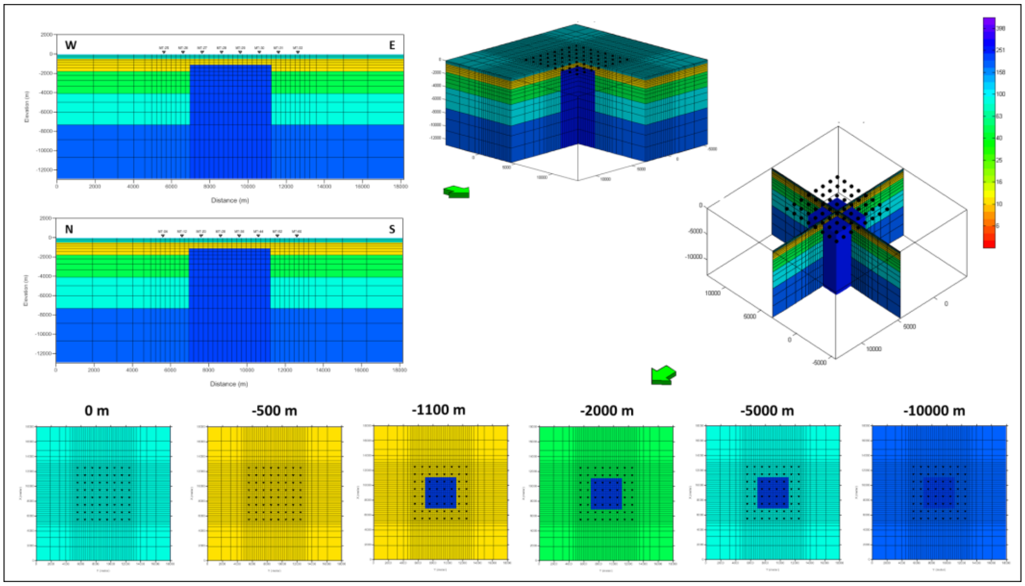

Figure 9. 3-D earth model.

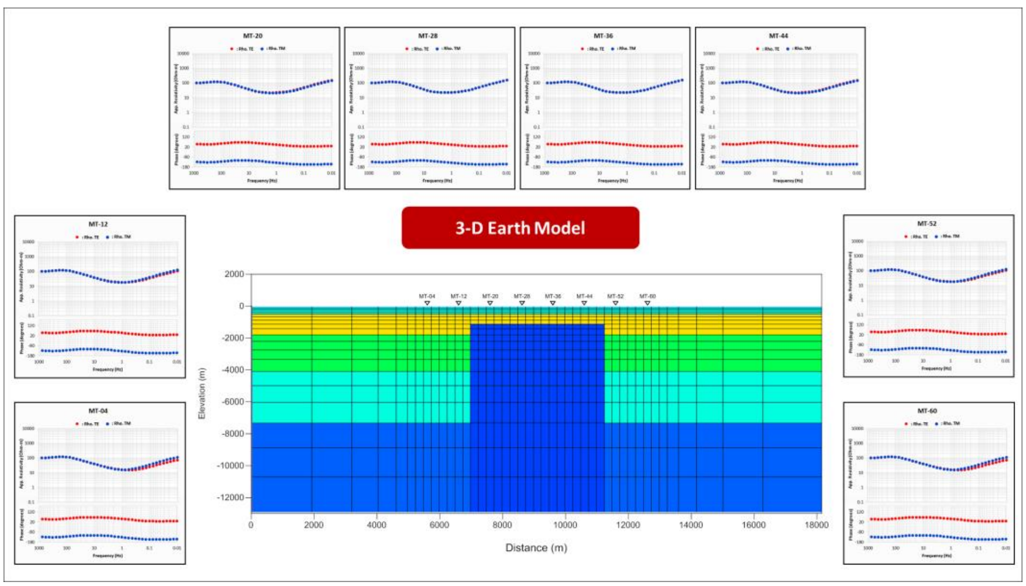

Figure 10. MT response of 3-D earth model derived from 3-D forward modeling.

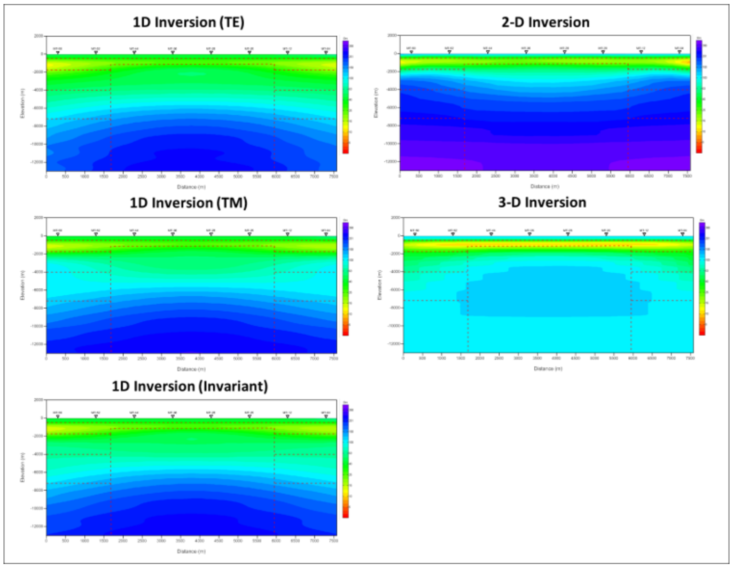

Figure 11. 1-D (TE/TM/Invariant), 2-D, & 3-D inversion result of 3-D earth model.

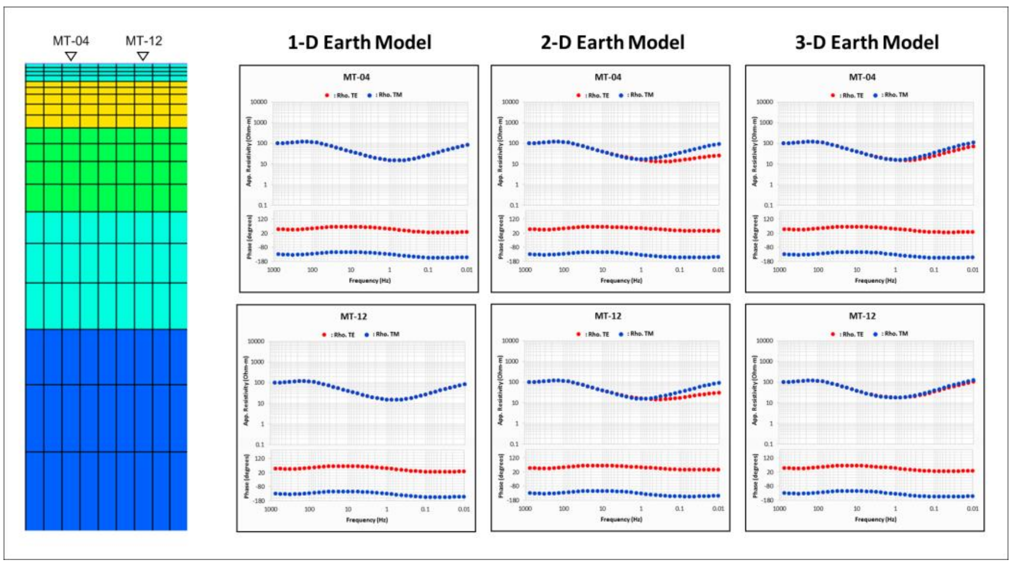

Figure 12. Comparison of MT response on MT-04 & MT-12 from 1-D, 2-D, and 3-D earth model.

DISCUSSION

The simulations show that the 3-D effect can affect the MT data. The 3-D effect appear when the lateral resistivity variation is exist like in 2-D and 3-D earth model. The same resistivity structure below each station can produce different MT response depend on the condition of resistivity variation in the surrounding area. This phenomena is shown by comparison of MT response in MT-04 and MT-12 like in figure 12. The MT inversion modeling of each model is also disturbed by the effect. All of MT inversion algorithm (1-D, 2-D, and 3-D inversion) was developed under certain assumption. Dimensionality of the model is the most important assumption that must be considered when perfoming inversion modeling.

The complexity of the real earth especially in geothermal area should be well considered. Simulation through synthetic MT data especially from 3-D earth model verified the influence of 3-D effect. The synthteic MT data from 3-D earth model has been affected by this effect. The 1-D and 2-D inversion result could not overcome the affected data which then produce unreliable resistivity model. Application of 3-D inversion to the MT data have effectively resolved the problem. Accordingly, MT data in complex geological structure like in geothermal area should be approached by 3-D inversion.

CONCLUSIONS

The simulation of 3-D effect in MT data using several synthetic model have been clearly identify the effect of lateral resistivity variation on MT response. MT response in one station not only influenced by resistivity structure below the station but also resistivity variation in the surrounding area. The different response of TE & TM mode in MT data could indicate the presence of complex resistivity structure around the area.

Moreover, the 3-D effect could not be overcome by every inversion approach. There is a correlation between dimensionality of earth model and the inversion approach. 1-D inversion would be appropiate to be applied for 1-D earth model. The same characteristic also occur in 2-D and 3-D inversion that could produce more reliable inversion model for 2-D and 3-D earth model respectively.

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