Layer Stripping in Magnetotellurics (MT) for Enhancement of Resistivity Change Effect in Reservoir: Equivalence Analysis

Hendra Grandis[1], Warsa[1] & Prihadi Sumintadireja[2]

[1]Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung,
Jalan Ganesha 10, Bandung 40132, Indonesia
[2]Faculty of Earth Science and Technology, Institut Teknologi Bandung,
Jalan Ganesha 10, Bandung 40132, Indonesia
*E-mail: grandis@geoph.itb.ac.id

Highlights:

- The possibility to use the magnetotellurics (MT) for monitoring of reservoirs (oil and gas, geothermal).
- Alternative algorithms for 1D MT forward modeling and layer stripping that allow simulation and enhancement of a reservoir's resistivity-change effects.
- The use of the Monte Carlo method for error analysis.
- Baseline EM geophysical survey result for a future CCS project.

Abstract. Magnetotellurics (MT) can be applied to monitor resistivity change at depth that is for example due to fluid injection in enhanced oil recovery or CO_2 storage. The observed MT data changes at the surface may be insignificant, but the effect can be enhanced using the layer stripping method, i.e. calculating MT data changes that would be observed at depth based on data from the surface. Two well-known formulas for MT 1D forward modeling were reformulated to allow for calculation of the impedance at depth based on the impedance at the surface. We applied the layer stripping technique to synthetic data associated with models that were representative of a likely CO_2 storage site. We also used an equivalent model and the Monte Carlo approach to estimate the sensitivity of the method to cope with the uncertainty of the host model and the input data. The layer stripping calculation has the greatest uncertainty at short periods, where the real and imaginary parts of the complex impedance tend to be equal, i.e. an homogeneous medium response. The layer stripping technique should be used with great caution based on a relatively precise 1D host model.

Keywords: *alternative MT modeling; anomaly enhancement; MT impedance; resistivity monitoring; time lapse.*

1 Introduction

The magnetotelluric method (MT) is an electromagnetic (EM) sounding technique that can be used to estimate subsurface resistivity variation by employing natural EM fields as the primary source. With its wide range of applications, depending on the period range and hence the penetration or

Received June 22nd, 2019, Revised February 4th, 2020, Accepted for publication March 26th, 2020.
 ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2020.52.2.9

investigation depth, MT is commonly used in mineral [1,2] and geothermal [3,4] explorations. To a lesser extent, due to its relatively low vertical resolution compared to the seismic method, MT is also used in oil and gas exploration [5,6]. The ineffectiveness of MT in resolving thin layers at depth is closely related to the diffusive character of EM fields. Because of this, the applicability of MT for monitoring of resistivity changes at depth is limited, as briefly discussed by Ogaya, *et al.* [7]. However, the use of MT for monitoring purposes has shown encouraging results [7,8].

The resistivity perturbation of a reservoir (oil, gas, geothermal) at depth often leads to insignificant changes in MT data (apparent resistivity and phase) at the surface. In the case of resistivity changes that occur at a limited depth with a well-defined host, analysis using a layered or 1D model can be considered appropriate. In this paper, we follow Ogaya, *et al*. [7] in analyzing the layer stripping approach to enhance the MT signature due to resistivity changes at depth. The host medium is assumed to be known as 1D and the resistivity change occurs in only one of the layers. The well-known recursive formula [9] and its alternative using matrix multiplication [10] for 1D MT forward modeling were rearranged to obtain the layer stripping formula, i.e. to calculate the impedance at depth from the impedance in the upper layer. The resulting layer stripping algorithms were applied to synthetic data from models representative of a likely CO_2 storage site [7] as well as from a future CO_2 storage site in Gundih field, East Java, Indonesia [11]. We used equivalent models and the Monte Carlo approach to estimate the uncertainty of the results with respect to the 1D host model and data uncertainties.

2 Layer Stripping Technique

2.1 Equivalence of the formulas

The analytical formula to calculate impedance at the surface of a model consisting of N layers with resistivity and thickness, ρ_j and h_j ; j = 1, 2, ..., N, constructs the 1D MT forward model. In early works on MT 1D modeling, the analytical formula for the impedance at the surface of a layered model involved hyperbolic tangent or cotangent functions of complex quantities [12,13]. However, the original expression of hyperbolic geometric functions with exponential functions is more appropriate for calculation using a computer. Furthermore, the recursive formula proposed by Pedersen and Hermance [9] was devised to avoid numerical instabilities by using exponential functions with only negative arguments and ratios with a non-zero denominator. The MT forward modeling for a layered model or a 1D model consists of calculating the impedance at the j-th layer, Z_j, as a function of its resistivity ρ_j and thickness h_j and the impedance at the (j+1)-th layer, Z_{j+1}, hence the term recursive, as follows:

$$Z_j = Z_{0j} \frac{1 - R_j \exp(-2k_j h_j)}{1 + R_j \exp(-2k_j h_j)} \tag{1}$$

where $\omega = 2\pi/T$ with T is the period and $\mu_0 = 4\pi\ 10^{-7}$ (all in SI) is the free space magnetic permeability. The characteristic or intrinsic impedance Z_{0j} and the EM wave number k_j are respectively defined by

$$Z_{0j} = \sqrt{i\omega\mu_0\rho_j} \quad \text{and} \quad k_j = \sqrt{\frac{i\omega\mu_0}{\rho_j}}. \tag{2}$$

In Eq. (1) R_j contains the impedance of the next (j+1)-th layer, expressed as

$$R_j = \frac{Z_{0j} - Z_{j+1}}{Z_{0j} + Z_{j+1}}. \tag{3}$$

The algorithm starts with the last (N-th) layer's impedance and proceeds upwards to obtain the impedance of the first layer, Z_1, at the surface of the layered model. The apparent resistivity ρ_a and phase ϕ as a function of period are then calculated from Z_1 by using the well-known Cagniard-Tikhonov formula [14]:

$$\rho_a = \frac{1}{\omega\mu_0} |Z_1|^2 \ ; \ \phi = \tan^{-1}\left(\frac{\operatorname{Im} Z_1}{\operatorname{Re} Z_1}\right). \tag{4}$$

Rearranging the terms in Eq. (1) results in another recursive formula for calculation of the impedance of a layer at depth from the impedance at a shallower layer, i.e. to obtain Z_{j+1} from Z_j:

$$Z_{j+1} = Z_{0j} \frac{1 - R_j \exp(-2k_j h_j)}{1 + R_j \exp(-2k_j h_j)}, \tag{5}$$

with a different expression for R_j:

$$R_j = \frac{Z_{0j} - Z_j}{Z_{0j} + Z_j}. \tag{6}$$

Eqs. (5) and (6) allow calculation of the impedance at any layer at depth from the impedance at the surface of the layered model (Z_1), i.e. the layer stripping algorithm.

As an alternative to the recursive formula in Eq. (1), following Ward and Hohmann [15], Grandis [10] proposed an algorithm for 1D MT forward modeling by using a matrix multiplication formula. With similar variables defined as before, the orthogonal electric E_x and magnetic H_y fields at two consecutive layers are represented by

$$\begin{pmatrix} E_{x,j} \\ H_{y,j} \end{pmatrix} = \begin{pmatrix} 1+\exp(-2k_j h_j) & Z_{0j}\,(1-\exp(-2k_j h_j)) \\ Z_{0j}^{-1}\,(1-\exp(-2k_j h_j)) & 1+\exp(-2k_j h_j) \end{pmatrix} \begin{pmatrix} E_{x,j+1} \\ H_{y,j+1} \end{pmatrix}$$

$$\begin{pmatrix} E_{x,j} \\ H_{y,j} \end{pmatrix} = \mathbf{T}_j \begin{pmatrix} E_{x,j+1} \\ H_{y,j+1} \end{pmatrix}. \tag{7}$$

where $\mathbf{T}_j$ is a 2 by 2 transfer matrix defined solely by parameters of the j-th layer (ρ_j and h_j). A successive multiplication of the transfer matrices relates the electric and magnetic fields at the surface to those at the last (N-th) layer, i.e.

$$\begin{pmatrix} E_{x,1} \\ H_{y,1} \end{pmatrix} = \prod_{j=1}^{N-1} \underline{\mathbf{T}}_j \begin{pmatrix} E_{x,N} \\ H_{y,N} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} E_{x,N} \\ H_{y,N} \end{pmatrix}. \tag{8}$$

Hence, the impedance at the surface of an N-layered model, i.e. $E_{x,1}/H_{y,1}$ can be calculated from

$$Z_1 = \frac{S_{11}\,Z_{0N} + S_{12}}{S_{21}\,Z_{0N} + S_{22}}. \tag{9}$$

where Z_{0N} is used to represent $E_{x,N}/H_{y,N}$, i.e. the characteristic or intrinsic impedance of the last layer.

Forward multiplication of Eq. (8) with the inverse matrix of $\mathbf{T}_1$ results in the EM fields at the 2nd layer, and so forth. The impedance at the j-th layer at depth can be obtained from the impedance at the surface by using the alternative layer stripping formula, as follows:

$$Z_j = \frac{S_{11}^*\,Z_1 + S_{12}^*}{S_{21}^*\,Z_1 + S_{22}^*} \;;\; \begin{pmatrix} S_{11}^* & S_{12}^* \\ S_{21}^* & S_{22}^* \end{pmatrix} = \prod_{k=j-1}^{1} (\underline{\mathbf{T}}_k)^{-1} \tag{10}$$

where in Eq. (10), inversion of 2 by 2 transfer matrices are involved and assumed to be non-singular. Similar to Eqs. (5) and (6), Eq. (10) can be used to calculate the impedance at any layer at depth, Z_j, from the impedance at the first layer, Z_1, given the model parameters of the other layers.

Both recursive and matrix multiplication formulas for layer stripping are in fact analytic and lead to almost exactly the same results. In what follows, the layer stripping results are presented only from the application of the recursive formula, i.e. Eqs. (5) and (6).

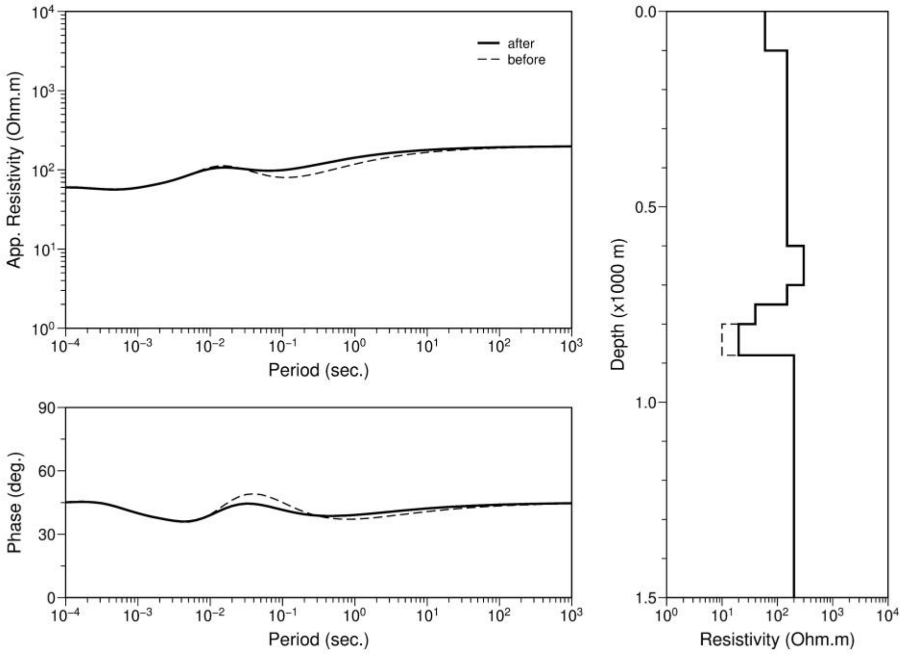
2.2 Application to Synthetic Data

Ogaya, *et al.* [7] tested their layer stripping algorithm on synthetic data that realistically represented a geo-electrical structure of a likely CO_2 storage site. We used the same synthetic 1D model (Figure 1(b)) to test our algorithms with both recursive and matrix multiplication formulas. The 1D model consisted of seven layers with the model parameters presented in Table 1 along with the lithology associated with each layer. The reservoir is at the 6th layer (100 m thick) and changed from 10 Ohm.m to 20 Ohm.m associated with gas injection. Figure 1(a) shows a comparison of the MT apparent resistivity and phase sounding curves at the surface of the model due to resistivity change. The synthetic model response was calculated in a period range of 10^{-4} to 10^{3} sec at 10 points per decade. The MT data changes in terms of the apparent resistivity and phase sounding curves at the surface were obviously not significant.

Table 1 Model parameters of the 1D model used to test the algorithms.

Layer	Resistivity (Ohm.m)	Thickness (m)	Remarks
1	60	100	Sediment
2	150	500	Siliciclastic
3	300	100	Limestone
4	150	50	Siliciclastic
5	40	50	Marly seal
6	10	100	Saline aquifer
7	200	-	Basement

To enhance the MT response due to the resistivity change from 10 Ohm.m to 20 Ohm.m of the reservoir (6th layer), the layer stripping technique was applied to the synthetic data presented in Figure 1(a). This is equivalent to obtaining MT data at the surface of the reservoir. For reference and for comparison, the MT sounding curves of a model consisting of only layers 6 and 7 (i.e. a two-layer model) are presented in Figure 2(a), where the upper layer is changed from 10 Ohm.m to 20 Ohm.m. In general, the layer stripping process is unstable for periods less than 0.0003 sec. The impedance at such short periods is very close to the response of a homogeneous medium, where real and imaginary parts of the impedance are almost equal. As shown in Figure 2(b), the layer stripping results were quite identical to the reference (see Figure 2(a)) at periods longer than 0.0003 sec.



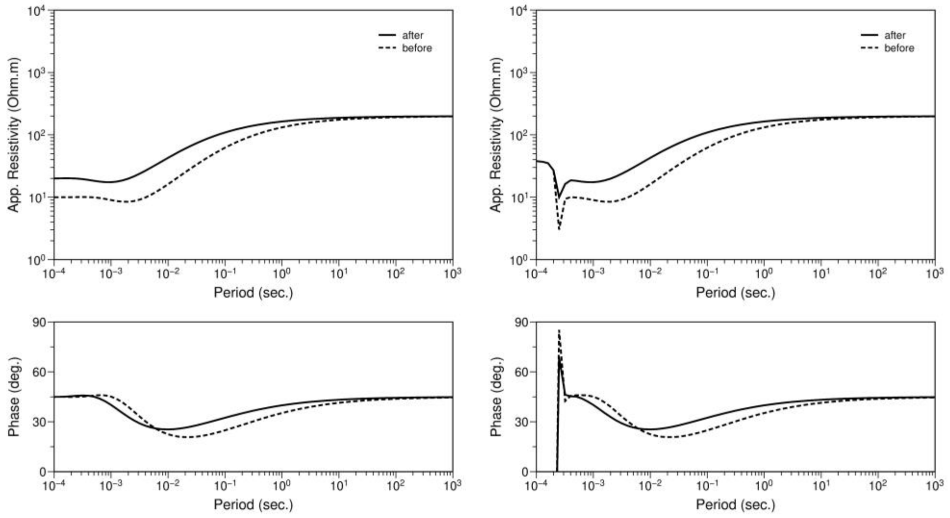
(a) (b)

Figure 1 (a) Calculated MT sounding curves at the surface of the 1D model shown in (b) with the resistivity change of the 6th layer from 10 Ohm.m (dashed) to 20 Ohm.m (full line), (b) 1D synthetic model similar to Ogaya *et al*. [7] used to test the layer stripping algorithm.

3 Uncertainty and Equivalence Model Analysis

3.1 Uncertainty Analysis

Ogaya, *et al.* [7] describe the analytic expressions for apparent resistivity and phase errors from the layer stripping calculations. With only a 1% error rate for the surface impedance (Z_1), errors for the impedance at depth were quite large, especially for a short period range. We also tested the error propagation in the layer stripping calculations by using the Monte Carlo method [16,17]. A large number of synthetic data were randomly generated within 1% standard deviation of the impedance (real and imaginary parts), associated with the above model (see Figure 1(b). The maximum and minimum values from the layer stripping calculations are considered the error margin, or error envelope, of the layer stripping results.



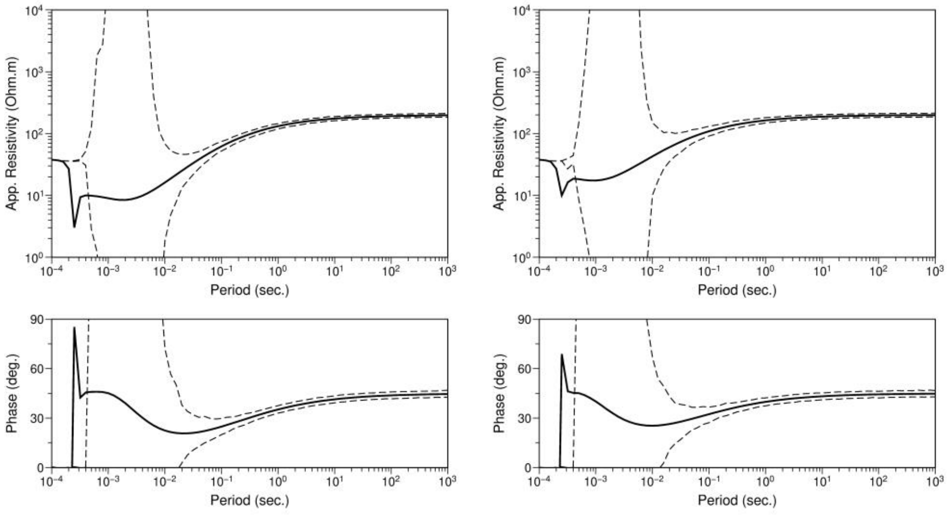
(a) (b)

Figure 2 (a) Calculated MT sounding curves showing resistivity change of the reservoir layer from 10 Ohm.m (dashed) to 20 Ohm.m (full line) of a two-layer model consisting of only layers 6 and 7 (see Figure 1(b)), (b) MT sounding curves at the surface of the 6th layer obtained from the layer stripping with the input data shown in Figure 1(a).

Tests with 1 and 10 million random samples were performed and showed the convergence of the Monte Carlo technique with large numbers of samples. The instability of the layer stripping calculation at very short periods (less than 0.0003 sec) led to undefined uncertainties represented by coincidence of the maximum and the minimum envelope of uncertainties, especially for apparent resistivity (Figure 3). In general, our results from the stochastic simulations were in accordance with the analytic error estimation of Ogaya, *et al.* [7].

3.2 Equivalence Analysis

The layer stripping approach assumes a known 1D model. To test the effect of erroneous 1D model parameters on the layer stripping method, we used an equivalent model with only 4 layers as the known 1D model. We assumed that layers 2, 3, 4 and 5 in the synthetic model (Figure 1(a)) could be replaced by an equivalent layer with the same total conductance. We used the following 4-layer equivalent model: (1) 60 Ohm.m and 100 m thick, (2) 150 Ohm.m and 690 m thick, (3) 10 Ohm.m and 85 m thick, and (4) 200 Ohm.m as the basement. The choice of the thicknesses of layer 2 and layer 3 was intended to obtain the responses of both 4-layer and 7-layer synthetic models within 1% RMS difference.



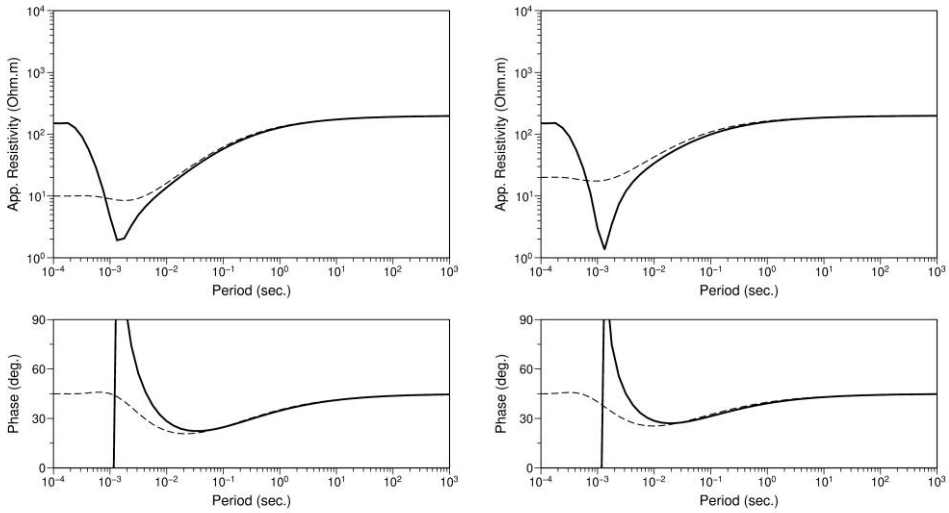
(a) (b)

Figure 3 Layer stripping results from synthetic data with uncertainties plotted as the minimum and maximum envelope (dashed line) due to an input data error rate of 1% for resistivity of the 6th layer changing from 10 Ohm.m (a) to 20 Ohm.m (b).

The layer stripping technique was applied to observe a resistivity change from 10 Ohm.m to 20 Ohm.m in the reservoir as above, i.e. in the 3-rd layer of the 4-layer model. In this case, the input data were the response of the original 7-layer model (see Figure 1(a)). The results from the equivalent 4-layer model (Figure 4) deviated from the correct ones at short periods (less than 0.01 sec.) For the rest of the period range, the layer stripping results could be considered acceptable, i.e. they had a good match with the reference curves. The phase curves were the most affected by the erroneous 1D model. It is obvious that such deviations are related to error propagation, which is considerably higher at shorter periods (see Figure 4). Therefore, the application of the layer stripping method must take such limitations into account. The sounding curves from layer stripping before and after resistivity change in the reservoir showed relatively significant differences compared to the sounding curves at the surface.

4 Application to 'Field' Data

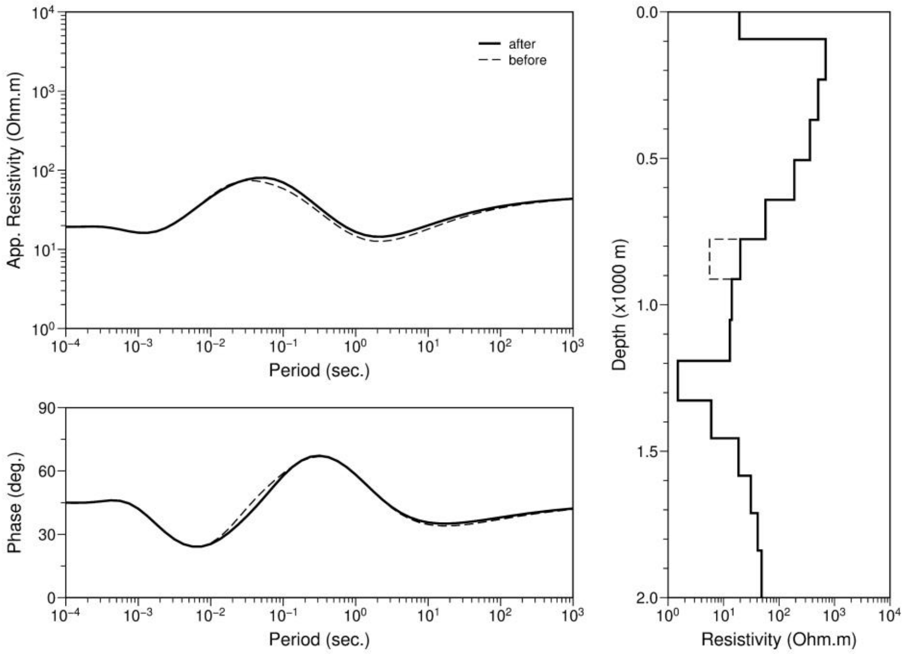
The Gundih Field in East Java is planned as the location for the first CCS (Carbon Capture and Storage) project in Indonesia in the near future. Detailed reservoir characterization studies have been done, mainly based on existing seismic and geological data [11]. At the present stage of the project, a magnetotelluric study has not been performed yet, but a transient electromagnetic (TEM) survey was done in 2017 with the objective of obtaining a baseline resistivity model before CO_2 injection [18,19]. We used the result of 1D TEM modeling at station E0N100 as a representation of the subsurface conditions before injection. The shallow reservoir that was proposed as the CO_2 injection target is a shale layer of the Ngrayong formation, estimated to be at about 800 m depth and with a resistivity of about 5.6 Ohm.m. A deeper reservoir, estimated at 1200 m depth and with a resistivity of 1.5 Ohm.m, was not targeted for CO_2 injection in this study. It is supposed that the shallower reservoir would have a resistivity of 20 Ohm.m after the injection.



(a) (b)

Figure 4 Layer stripping results from synthetic data with equivalent 4-layer model compared to original 7-layer model (dashed line) with the resistivity of the reservoir layer changing from 10 Ohm.m (a) to 20 Ohm.m (b).

1D MT forward modeling was done to obtain an MT data set representative of the conditions before and after reinjection [see Figure 5]. As expected, having the same 1D model for generating realistic synthetic data and layer stripping led to results with the same characteristics as before, i.e. using the synthetic model from Ogaya, *et al.* [7]. Therefore, we added 1% normally distributed noise to the synthetic data to obtain more realistic results. A comparison was then made between the layer stripping results from the synthetic data with and without noise added, as shown in Figure 6. The results confirmed that the part most influenced by the presence of noise is the short period range, i.e. less than 0.01 sec. This short period range also had higher uncertainties according to the error analysis, both done analytically [7] and stochastically. Higher-level noise would lead to a more limited period range for the results to be reliable.



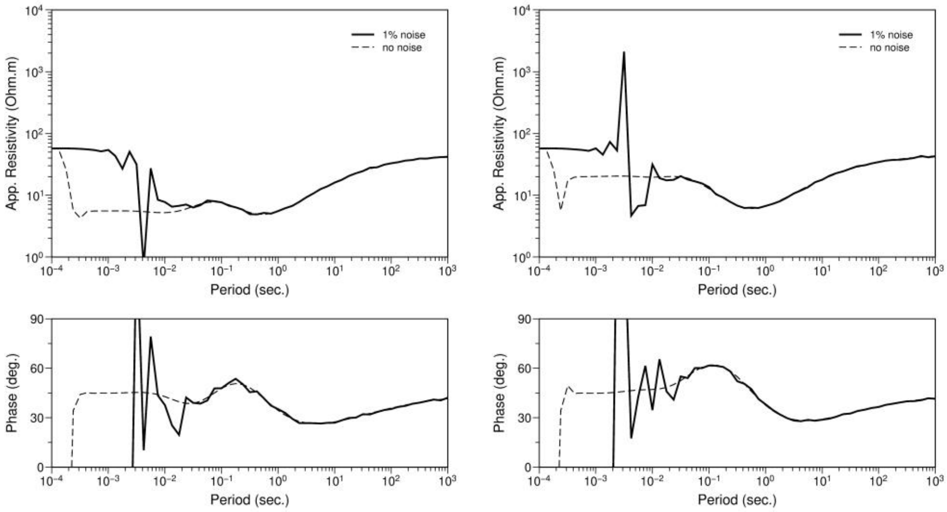
(a) (b)

Figure 5 (a) Synthetic MT data associated with a representative model of the Gundih field, Indonesia before and after injection, (b) 1D model obtained from 1D inversion of TEM data from station E0N100 used to generate the synthetic data in (a).

5 Conclusion

We have presented a layer stripping method that enhances resistivity change at depth in a 1D model. The method can be implemented by using two types of formulas, each related to a different 1D forward modeling approach, i.e. using a recursive formula and matrix multiplication respectively. We consider the proposed formulas to be more explicit compared to the original one; they can be directly implemented in computer programming, where the recursive character of the formula is expressed in nested functions [7]. Initially, the motivation of using the matrix multiplication formula for layer stripping was to obtain results with less error propagation from the input uncertainties (i.e. the surface impedance) related to the use of successive inversion and multiplication of the transfer matrices. In fact, both methods led to identical results, including the characteristics of error propagation in the apparent resistivity and phase sounding curves after layer stripping.

The MT layer stripping technique should be applied with caution since the error propagation is large, especially at shorter periods, even with an error rate of only 1% in the input data (MT impedance measured at the surface). The layer stripping result is also sensitive to errors from the 1D model, which is usually assumed to be known. In this case, data from a well (resistivity log) or other sources can be used to define the 1D model as detailed and as precise as possible. Although the technique in the 1D case presented in this paper overly simplified the real problem, it provides a tool for baseline study and also for supplying test parameters for reservoir monitoring purposes.



(a) (b)

Figure 6 Comparisons of layer stripping results from realistic synthetic data without and with 1% Gaussian noise for Gundih Field, Indonesia. The reservoir at 800 m depth has a resistivity change from 5.5 Ohm.m (a) to 20 Ohm.m (b).

Acknowledgments

The research was supported by ITB Research Grant 2020. The Gundih Carbon Capture and Storage (CCS) Project Team is highly appreciated for their collaborative effort in acquiring the transient electromagnetic (TEM) field data.

References

[1] Zhang, P. & Chouteau, M., *The Use of Magnetotellurics for Mineral Exploration: an Experiment in the Chibougamau Region of Quebec*, Can. J. Earth Sci., **29**(4), pp. 621-635, 1992.

[2] Farquharson, C.G. & Craven, J.A., *Three-Dimensional Inversion of Magnetotelluric Data for Mineral Exploration: An Example from the Mcarthur River Uranium Deposit, Saskatchewan, Canada*, J. Appl. Geophys., **68**(4), pp. 450-458, 2009.

[3] Pellerin, L., Johnston, J.M. & Hohmann, G.W., *A Numerical Evaluation of Electromagnetic Methods in Geothermal Exploration*, Geophysics, **61**(1), pp. 121-130, 1997.

[4] Muñoz, G., *Exploring for Geothermal Resources with Electro-Magnetic Methods*, Surv. Geophys., **35**(1), pp. 101-122, 2014.

[5] Mitsuhata, Y., Matsuo, K. & Minegishi M., *Magnetotelluric Survey for Exploration of a Volcanic-Rock Reservoir in the Yurihara Oil and Gas Field, Japan*, Geophys. Prospect., **47**(2), pp.195-218, 1999.

[6] Connell, D. & Key K., *A Numerical Comparison of Time and Frequency-Domain Marine Electromagnetic Methods for Hydrocarbon Exploration in Shallow Water*, Geophys. Prospect., **61**(1), pp. 187-199, 2013.

[7] Ogaya, X., Ledo, J., Queralt, P., Jones, A.G. & Marcuello, A., *A Layer Stripping Approach for Monitoring Resistivity Variations Using Surface Magnetotelluric Responses*, J. Appl. Geophys., **132**, pp. 100-115, 2016.

[8] Rees, N., Carter, S., Heinson, G. & Krieger, L., *Monitoring Shale Gas Resources in the Cooper Basin Using Magnetotellurics*, Geophysics, **81**(6), pp. E423-E432, 2016.

[9] Pedersen, J. & Hermance, J.F., *Least Squares Inversion of One-Dimensional Magnetotelluric Data: An Assessment of Procedures Employed by Brown University*, Surv. Geophys., **8**(2), pp. 187-231, 1986.

[10] Grandis, H., *an Alternative Algorithm for One-Dimensional Magneto-telluric Response Calculation*. Comp. Geosci., **25**, pp. 119-125, 1999.

[11] Tsuji, T. & Gundih CCS project team, *Reservoir Characterization for Site Selection in the Gundih CCS Project, Indonesia*, Energy Procedia, **63**, pp. 6335-6343, 2014.

[12] Zhdanov, M.S. & Keller, G.V., *the Geoelectrical Methods in Geophysical Exploration*, Elsevier, 1994.

[13] Zhdanov, M.S., *Geophysical Electromagnetic Theory and Methods*, 2nd ed., Elsevier, 2017.

[14] Simpson, F. & Bahr, K., *Practical Magnetotellurics*, Cambridge, Cambridge University Press, 2005.

[15] Ward S.H. & Hohmann, G.W., *Electromagnetic Theory for Geophysical Applications, Electromagnetic Methods in Applied Geophysics*,

Nabighian, M.N., ed., Society of Exploration Geophysicists, pp. 131-311, 1988.

[16] Warsa & Grandis, H., *Sensitivity Study of 3-D modeling for Multi-D Inversion of surface NMR*, AIP Conference Proceedings, **1454**, pp. 130-133, 2011.

[17] Irawan, D., Grandis, H. & Sumintadireja, P., *Quasi-2D Resistivity Model From Inversion of Vertical Electrical Sounding (VES) Data Using Guided Random Search Algorithm*, J. Math. Fund. Sci., **47**(3), pp. 269-280, 2015.

[18] Srigutomo, W., Warsa, Sule, M.R., Trimadona, Prasetyo, D., Saito, A., Nakayama, K., Hato, M. Prasetyo, A. & Widarto, D.S., *Time-Domain Electromagnetic (TDEM) Baseline Survey for CCS in Gundih Area, Central Java, Indonesia*. Proceedings 12th SEGJ International Symposium, Tokyo, Japan, 2015.

[19] Prasetyo, D., *Non-Linear Inversion Modeling of Transient Electro-magnetic (TEM) Data for Hydrocarbon Reservoir Characterization* (in Indonesian with English abstract), Master Thesis, Geophysical Engineering Program, Institut Teknologi Bandung, Bandung, Indonesia, 2017.