چهل و دومین گردهمایی (همایش) ملی
علوم زمین
The 42nd National
Geosciences Congress
www.geoconf.ir
ISC

Two-Dimensional Magnetotelluric Data modeling of the Sabalan geothermal field using REBOCC and MT2DInvMatlab codes

Gholam- Abbas Fanaee Kheirabad

Assistant Professor, Department of Mining Engineering, Birjand University of Technology, Birjand, Iran
afanaee@birjandut.ac.ir

Abstract

In this paper the modelling of Magnetotelluric (MT) data of Sabalan geothermal was undertaken to evaluate the resistivity models at the shallow depth and in the upper layers of thermal reservoir. For this purpose, a profile with the length of approximately 10 km include seven MT measuring stations selected and two-dimensional (2D) modelling source codes named the reduced based Occam (REBOCC) and the MT2DIinvMatlab inversion has been applied. The data points were carefully selected between frequency range 0.01- 132 Hz. In order to explain the mechanism of the geothermal reservoirs, some global conceptual model is presented that each of these models is valid for the interpretation of geothermal phenomena in a particular area. MT2DInvMatlab inversion source code prepared based on the finite elements (FEM) method for forward modelling. Inversion parameters as an Input file and appropriate mesh blocks design should prepared before starting the modelling and inversion. After setting up the model parameter, 2D inversion of the Sabalan magnetotelluric data has been performed using smoothness–constrained least square methods with a spatially regularization parameter estimation. The ACB (Active Constraint Balancing) algorithm employed to stabilize the model. Both apparent resistivity and phase data has been used to have model with minimum misfit for TM mode data. REBOCC is the second inversion program using for 2-D modeling. The resulting models reveal the presence of a resistive cover layer (Cap-rock) underlain by an anomalous conductive layer and other geological structures such as fluid-filled faults in about 500-1000 m below the ground surface. A very low resistivity (3-5 ohm-m) feature at the depths below 2000 m, bounded by two more resistive (100-500 ohm-m) features that interpreted as the main reservoir of the geothermal system in the area. At shallow depths, the resistivity model obtained from the MT data is consistent with the general conceptual resistivity model proposed for high-temperature geothermal systems.

Keywords: Magnetotellurics, Geothermal exploration, REBOCC, MT2DInvMatlab, Sabalan

1. Introduction

Geothermal resources are ideal targets for electromagnetic (EM) methods since they produce strong variations in underground electrical resistivity. In thermal areas, the electrical resistivity is substantially different form and generally lower than in areas with colder subsurface temperature [1].

The most productive areas of Sabalan geothermal field were explored in November 2007, to investigate any consistency between the resistivity models of the area and the conceptual resistivity model presented for high temperature geothermal fields [2].

Resistivity in geothermal areas is related to the presence of hydrothermal alteration products, since they contain clays. The resistivity can be reduced considerably when the clay minerals are broadly distributed [3]. The basic principles of the MT method were introduced by Tikhonov [4] and Cagniard [5]. MT sounding curves show a 2D effect with a clear separation between the curve where the electric field parallel to the strike (TE mode), and the curve related to current circulation normal to the strike (TM mode).

The TM mode data often used for 2-D modelling of MT data in geothermal field studies because the TM mode apparent resistivities and phases are better fitted than the TE mode, as a consequence of the inherently inductive nature of the 2D TE response in a 3-D geothermal field structures. However, the apparent resistivity and phase data are also well fitted in the joint inversion of TM and TE mode data.

The data at some sites and frequencies show high skew values that originate from either galvanic distortion or 3D subsurface structures. In cases where MT data display overall 2D characteristics despite some 3D affects, results obtained by using 2-D inversion algorithms can be valid [6]. At the current study the MT data were analysed and modelled using MT2DInvMatlab and REBOCC inversion source codes that use the method of finite elements (FEM) and finite difference (FD) for forward modelling respectively.

2. Geothermal Energy prospects in Sabalan

Exploration for geothermal resources in the Sabalan mountains of north-western Iran, undertaken in the summer of 1998, identified several low resistivity anomalies around the flanks of the volcanic complex that are worth investigating by deep drill-holes. Interpretation of 212 magnetotelluric soundings was assisted by the use of coincident TDEM [7], [8] and the geological setting and the geochemical character of thermal springs in the Sabalan area is discussed in detail elsewhere [9].

Structurally, the Sabalan area is located in a very complex compressional tectonic zone, on the NE moving South Caspian sub-plate, near the junction of the Eurasian, Iranian, and Arabian plates. Two dimensional cross-sections have been compiled from the layered models, through the main areas of interest.

Interpretation of the layered resistivities confirm the conceptual geothermal and hydrological models of the Sabalan area and the resistivity structure of the region surrounding Sabalan to enhance different aspects of the layered models. The obtained models successfully identified several low resistivity anomalies around the flanks of the Sabalan volcanic that most significant, from a geothermal perspective, are situated near the hot springs and the selected profile [10].

3. The Magnetotelluric Method

The principle behind electromagnetic (EM) methods is governed by Maxwell's equations that describe the coupled set of electric and magnetic fields' change with time: changing electric currents create magnetic fields that in turn induce electric fields that drive new currents. Most EM techniques (controlled source audio magnetotellurics (CSAMT), TDEM, FDEM, GPR, and NMR) use a controlled artificial electromagnetic source as a primary field that induces a secondary magnetic field, while The Magnetotelluric Method (MT) methods use the earth's natural electromagnetic field as source signal [11].

EM methods can be used for exploration and monitoring of circulating fluids in reservoirs or faults and thus provide important information about their activity and fluid content. As the phase change of pore fluid (boiling/condensing) in fractured rocks can result in resistivity changes that are more than one order of magnitude greater than those measured in intact rocks, EM methods can provide information of primary economic significance.

In addition, production-induced changes in resistivity provide valuable insights into the evolution of the host rock and resident fluids and thus into the sustainability of a reservoir.

In the MT method natural EM waves, generated by thunderstorm activity, provide signals with frequencies higher than 1 Hz, while frequencies lower than 1 Hz are caused by large-scale ionospheric currents created by the interaction between the solar wind and the magnetosphere [11].
The investigation depth is a function of the electrical resistivity ρ of the earth and angular frequency, ω, of the EM field. Since earth is a conductor, the electromagnetic wave is governed by a diffusion process in the earth. This implies that the field strengths attenuate (decrease exponentially) with depth. A reasonable measure of the penetration scale length is the skin depth δ, which corresponds to the depth at which the amplitude of the incident electromagnetic field has attenuated by a factor of 1/e.
A useful approximation for a uniform half-space of resistivity ρ is given as:

$$\delta \approx 500 \sqrt{\rho/f} \quad \text{(meters)} \qquad (1)$$

The skin depth relation shows that investigation depth depends not only on frequency but also on the resistivity of the subsoil.
Since TM mode typically suffers less 3D distortion than TE mode [12], we considered only the TM mode data for inversion. The MT transfer functions of TM-mode data were inverted to derive the 2D subsurface resistivity distribution by using the two algorithms MT2DinvMatlab and REBOCC for modelling and interpretation that describe in this paper.

3.1. MT2DinvMatlab Theory

Two-Dimensional (2D) inversion code MT2DinvMatlab [13] is an open-source MATLAB based software package for two-dimensional (2D) inversion of magnetotelluric (MT) data that seeks a smooth model with the minimum number of features required to fit the observed data. Forward modelling in MT2DInvMatlab, use the finite elements (FEM) method in order to calculate 2D MT responses of geological structures. The governing equations for the transverse electric (TE; E-parallel to the strike) and transverse magnetic (TM; H-parallel to the strike) modes of MT fields can be rewritten as:

$$\text{grad}\,(1/\tau\ \text{grad}\ V) = \gamma\, V \qquad (2)$$

After solving for V in Eq. (2) and following the standard procedure in FE formulation [14], we have the corresponding integral form by weighted residual method.
The MT 2D forward problem can be represented generally in a discrete form as:

$$d = G\,(m) \qquad (3)$$

where G is a forward modeling operator which is generally non-linear, m is a model parameter vector, and d is a model response (predicted data) vector. In this program, the smoothness-constrained least-squares inversion is adopted for solving the regularized inverse problems. Linearization of Eq. (3) and some manipulation yields:

$$\Delta m = (J^T J + \lambda^2 C^T C)^{-1} J^T \Delta d \qquad (4)$$

where Δd is the error or discrepancy vector between the observed and calculated data, Δm denotes the model updates to be obtained, J is the Jacobian matrix or sensitivity matrix of forward modelling operator G, C is a Laplacian (second-order) smoothness operator, and λ is a regularization parameter (Lagrangian multiplier) or trade-off parameter between model constraint and data misfit.
A spatially variable regularization parameter algorithm by Yi et al. [15] for smoothness constrained least squares inversion with ACB (active constraint balancing) algorithm has been implemented to obtain an optimal smoothness constraint. Also, smoothly varying topography into a forward model by deforming rectangular elements to quadrilateral elements with the elevation of the air and earth interface is available in MT2DinvMatlab. The normalized root mean square (R.M.S) or data misfit error achieved after 10 iterations was around 0.7 for TM mode data. The apparent resistivity and phase data and model responses from the inversion using MT2DinvMatlab code shown separately is shown in Figure 1.

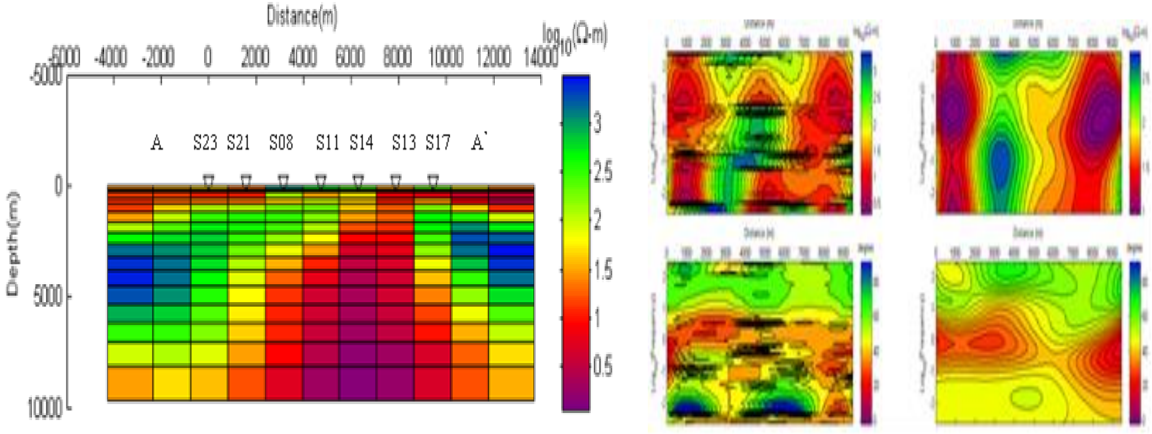

Figure 1. (a) The electrical resistivity model of TM mode data resulting from the MT2DInvMatlab inversion codes (left).
(b) TM-mode data and model responses of the MT2DInvMatlab inversion (right).

3.2. REBOOC Theory

Since MT data are smooth and redundant, a subset of the representers is typically sufficient to form the model without significant loss of detail. Computations required for constructing sensitivities and the size of matrices to be inverted can be significantly reduced by this approximation. We refer to this inversion as REBOCC, the reduced basis OCCAM's inversion.
The 2D inversion code of REBOCC by Siripunvaraporn and Egbert [16] was used to obtain the subsurface structure along the selected profile. The code seeks a smooth model with the minimum number of features required by the data. The REBOCC is generally faster and significantly faster than OCCAM [17].
In an alternative approach to improving computational efficiency is based on the observation that the updated inverse solution $\mathbf{m}_{k+1}$ in data space approach, the series of iterative approximate solutions is obtained as:

$$m_{k+1} - m = C_m J_k [\lambda C_d + J_k C_m J_k^T]^{-1} d_k^T \qquad (5)$$

A linear combination of the N columns of $C_\mathbf{m} \mathbf{J}_k$. In REBOCC sensitivities for a subset of K data are calculated (skipping every other frequency or every other site in a profile) and an approximate solution is sought as a linear combination of the corresponding K columns of $C_\mathbf{m} \mathbf{J}_k$ [17]. The apparent resistivity and phase data and model responses from the inversion using REBOCC code shown separately is shown in Figure 2.

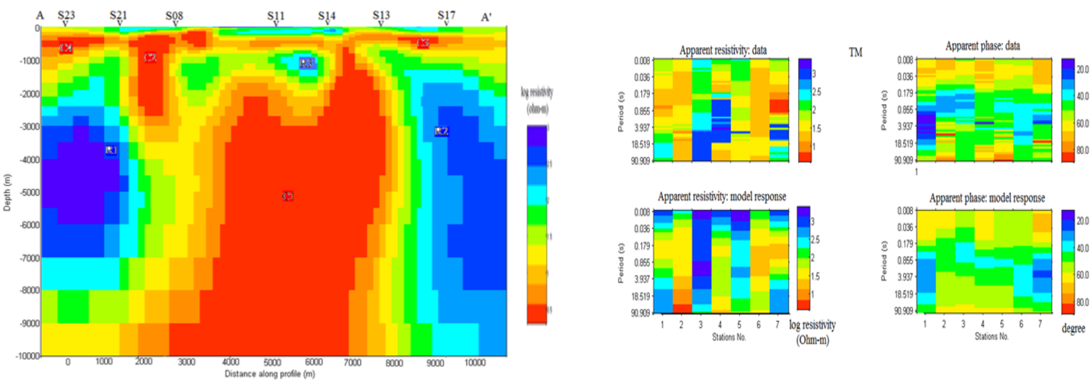

Figure. 2. (a) The electrical resistivity model of TM mode data resulting from the REBOCC inversion codes. C; conductive, R; resistive features (left).
(b) TM-mode data and model responses of the REBOCC 2D inversion (right).

4. Electrical Resistivity Models Interpretation

2D inversion yielded conductivity models with stable features, identifying the main geological units. The prominent structures in the resistivity model of TM mode data inversion in Figure 1& 2 and its relevance to the geothermal field are discussed below.

The obtained 2D resistivity structures are fairly like the previous results from 1998 data modeling ([2]; [10]). The resistive layer at the surface can clearly be interpreted as the geothermal cap rock. There are remarkable signatures as subsurface conductivity variations at depth**.**

At great depths there is a highly conductive (<5 ohm-m) structure that intrudes upwards to a depth of about 2.5 km in the middle of the profile and most naturally magmatic intrusions acting as a heat source for the geothermal system. This conductive structure is clearly constrained to the central part of the profile.

This conductive medium can be interpreted as either partial melt or a porous region with hot ionized fluids located on top of a magmatic heat source. Another peculiar feature of the section is the area beneath sites 8, 21 and sites 13 and 14, where the 2D models shows an abrupt transition to moderate resistivity values down to depths of 2-3 km where the deep conductive body begins. This would imply the presence of an almost vertical fluidized and/or altered fault zone connecting the shallow and deep conductors [9].

The main result obtained from the two inversion algorithms is compatible and show that the resistivity structure defined in the first 0.5–4 km is perfectly comparable to the structures found in literature as conceptual resistivity model of high-temperature geothermal systems [8].

5. Conclusion

The magnetotelluric method, with its ability to map deep conductive features can make a valuable role in the reconnaissance of deep geothermal systems in many geothermal areas. In this paper, electrical resistivity models obtained by using two inversion schemes REBOCC and MT2DInvMatlab in order to assess the location and depth of the three main parts of the Sabalan geothermal system.

We can notice that the two inversion codes give quite similar resistivity images, even though the detailed inversion parameters are not identical. We can also identify that the two programs give quite compatible results in the inversion for TM mode data.

One can also check regularization parameters, which are actually applied as a function of spatial coordinates in the inversion with MT2DInvMatlab. Besides the similarity of the inversion images, we can identify that the contrast in the inverted resistivity sections become more distinct when using REBOCC codes.

Acknowledgements

The author would like to thank Renewable Energy Organization of Iran (SUNA) for preparing the MT data of the case study.

References

[1] Oskooi, B., Pedersen, L.B., Smirnov, M., Árnason, K., Eysteinsson, H., Manzella, A., 2005.The deep geothermal structure of the Mid-Atlantic Ridge deduced from MT data in SW Iceland. Phys. Earth Planet. Inter. 150, 183–195.

[2] Talebi, B., 2006. Numerical modeling of the NW Sabalan geothermal field, Iran. Proc. Thirty-First Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California.

[3] Spichak V. and Manzella A. 2009. Electromagnetic sounding of geothermal zones. - Journal of Appl. Geophysics, 68 (4), 459-478.

[4] Tikhonov, A.N., 1950. On determining electrical characteristics of the deep layers of the Earth. Doklady Akademii Sel'skohozaÃjstvennyh Nauk 73, 295–297.

[5] Cagniard, L., 1953. Basic theory of the magnetotelluric method. Geophysics 18, 605–635.

[6] Ledo, J., 2005. 2D versus 3D magnetotelluric data interpretation: Surveys in Geophysics, 26,671-806.

[7] Fanaee Kheirabad, G. A., Oskooi, B., Porkhial, S., and Rahmani, M. R., 2010. Investigation of Sabalan geothermal field structure using Magnetotelluric data, Presented in 14th Geophysics Conference of Iran, Tehran, Iran.

[8] Fanaee kheirabad, G.A., Oskooi, B., 2011. Magnetotelluric interpretation of Sabalan geothermal field in northwest of Iran. Journal of the earth and space physics 37(3):1-11

[9] Fanaee, G.A., 2010. Electrical resisitivty model of Sabalan Geothermal field using Magnetotelluric data, PhD Thesis, Institute of Geophysics, University of Tehran.

[10] Fanaee Kheirabad, G. A., Oskooi, B., (2021) Two-dimensional magnetotelluric modeling of the Sabalan geothermal field, North-West Iran, Journal of the earth and space physics,46(4), 27-37

[11] Huenges, E., 2010, Geothermal Energy Systems: Exploration, Development, and Utilization 1st Edition, Kindle Edition

[12] Wannamaker, P.E., Hohmann, G., Ward, S., 1984. Magnetotelluric responses of three-dimensional bodies in layered earths. Geophysics 49, 1517–1533.

[13] Lee, S. K., Kim ,H,J., Song Y, Lee, C., 2009. MT2DInvMatlab- A program in MATLAB and FORTRAN for two-dimensional magnetotelluric inversion, Computer and Geoscience 35: 1722-1735

[14] Becker, E.B., Carey, G.F., Oden, J.T., 1981. Finite Elements: An Introduction. Prentice- Hall Inc., Englewood Cliffs, NJ, 255pp

[15] Yi, MJ., Kim, J. H., and Chung, S, H., 2003, Enhancing the resolving power of least squares inversion with active constraint balancing:Geophysics, 68, 931-941

[16] Siripunvaraporn, W., Egbert, G., 2000. An efficient data-subspace inversion method for 2D magnetotelluric data. Geophysics 65, 791–803.

[17] deGroot-Hedlin, C., Constable, S., 1990. Occam's inversion to generate smooth, two- dimensional models from magnetotelluric data. Geophysics 55, 1613–1624.