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Quasi-2D Resistivity Model from Inversion of Vertical Electrical Sounding (VES) Data for Preliminary Geothermal Prospecting

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ABSTRACT

Vertical Electrical Sounding (VES) using Schlumberger electrode configuration is practical in the field with rough topography. With moderate investigation depth, VES technique is still commonly performed in preliminary surveys of a geothermal prospect. This paper presents the guided random search algorithm for VES data inversion leading to a quasi-2D resistivity model. At every VES station, resistivities of a layered earth model with fixed thicknesses are selected from "a priori" resistivity values favoring lower misfit. In addition, a higher weight is associated to a resistivity value minimizing the variation of resistivities: (i) between layers at one station (vertical smoothness), and (ii) of the same layer at adjacent sounding sites (horizontal smoothness). Simultaneous inversions of original and interpolated VES data along a profile results in a quasi-2D smooth resistivity model of the subsurface. The algorithm was applied to invert synthetic data and was able to recover the synthetic model satisfactorily. The inversion result of field data from a geothermal field is in good agreement with known local geology of the survey area. The top of conductive cap rocks are well resolved at shallow to moderate depths (approximately 600 m) which are typical accessible target for a geothermal exploration at the preliminary stage using the geo-electrical method.

INTRODUCTION

The geo-electrical method is one of geophysical methods that can be used to infer the subsurface resistivity structure with relatively simple data acquisition and interpretation. Recent technology advances have led the use of digital multi-channel recording with multi-electrode system for the efficient and cost-effective 2D resistivity imaging technique. Furthermore, 2D resistivity inversion modeling has been done on a more routinely basis (Meju and Montague, 1995; Loke, 2003; White et al., 2003). However, the use of multi-electrode system is effective only for a shallow depth target such as in geo-technical and environmental studies (Dahlin, 1996; Delgado et al., 2006). For moderate depth target and for a survey area with difficult acces, the Vertical Electrical Sounding (VES) method especially using the Schlumberger electrode configuration is still preferred.

VES technique using Schlumberger electrode configuration has relatively deeper investigation depth compared to those using multi-electrode system for 2D resistivity imaging. It is also practical in the field with rough topography. To attain deeper target, only the outer electrodes (current electrodes, AB) need to be increased, while the inner electrodes (potential electrodes, MN) remain relarively fixed near the sounding point (Figure 1). In general, VES data are conveniently interpreted by using 1D modeling to obtain variation of the resistivity with depth (layered earth model) at every VES point. Then, correlation of 1D models at VES sites along a profile can be done to produce a quasi-2D resistivity image of the subsurface. In this perspective, we have proposed 1D inversion modeling of VES data using the guided random search method (Grandis and Irawan, 2012; Grandis et al., 2013). The use of the global search approach is intended to overcome difficulties in local or linearized approach of non-linear inverse problems.

Following Auken et al. (2005), we extend our previous approach to include both vertical and lateral smoothness constraints. While retaining the use of 1D modeling for VES data at every sounding site to simplify the problem, we can increase the continuity of layers in the resistivity section. The algorithm was applied to invert synthetic VES data associated with a simple model containing a low resistivity layer as a cap rock formation and also to real VES data from a known geothermal prospect.

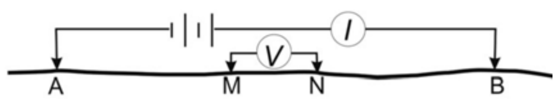

Figure 1. Schlumberger electrode configuration, A and B are current electrodes, M and N are potential electrodes.

METHOD

Consider a 1D earth model formed by a number of layers with thickness h_i and resistivities ρ_i, i = 1, 2, ..., N where N is the number of layers. We discretize the vertical section of the model into homogeneous intervals in the logarithmic scale, i.e. layers' thicknesses increase with depth, to represent the decreasing resolution with depth. For a large number of layers (20 or more) with fixed thicknesses, the model parameters to be estimated in the inversion are layers' resistivities. The possible "a priori" values for resistivities are R_j; j = 1, 2, ..., M which are discrete values regularly sampled in the logarithmic scale from 0.1 to 1000 Ohm.m representing conductive to resistive medium. A typical value for M is from 20 to 30.

The probability of R_j as the resistivity of the i-th layer ρ_i is expressed by:

$$P(R_j) = \exp(-E(\mathbf{m} \,|\, \rho_i = R_j)) \qquad (1)$$

where $E(\mathbf{m}|\rho_i = R_j)$ is the misfit related to a model $\mathbf{m} = [\rho_i]$ in which $\rho_i = R_j$ while resistivities of layers other than i-th layer are fixed at their current values. We use a typical algorithm to perform the 1D VES forward modeling in the calculation of the misfit (Ekinci and Demirci, 2008). Iterative updating of the model's resistivity is performed by selecting the resistivity value of a layer from R_j; j = 1, 2, ..., M with the probability $P(R_j)$ as weights. A resistivity value for a particular layer has higher probability if it is associated with lower misfit. Other resistivity values with higher misfits can still be selected as long as they have non-zero probabilities, they are only less probable. The algorithm can, in principle, avoid convergence to local minima and find optimum model associated with the global minimum. This guided random search method belongs to the global approach of inverse problem resolution since these is no need to calculate the gradient and its linearized approximation of the objective function (Sen and Stoffa, 1995).

Starting with a homogeneous model, the iterative resistivity updating of layers convergent to invariant models with low misfit. However, without any additional constrain applied, inverse models tend to be very arbitrary in terms of "geological structure". The models with response relatively good fit to the data exhibit high resistivity variations from layer to layer. This phenomenon can be associated with the equivalence problem, i.e. many different models can have theoretical responses at the same level of low misfit to the data (Sharma and Verma, 2011). In addition, the use of relatively thin layers, especially near the surface, adds the ambiguity in choosing the correct resistivity values for those layers. In such case, the misfit can not distinguish between many values of resitivities proposed.

In the first attemp to resolve the problem, an additional constraint was used in the algorithm. A smoothness constraint is introduced by minimizing resistivity variations from layer to layer in the 1D model, i.e. vertically. The resistivity variation from three consecutive layers around i-th layer at the k-th sounding point is defined by the following resistivity differences:

$$V = (\log\rho_{i-1}^{k} - \log\rho_{i}^{k})^2 + (\log\rho_{i+1}^{k} - \log\rho_{i}^{k})^2 \qquad (2)$$

Incorporating such vertical smoothness constraint in the inversion algorithm results in better optimum models. The inverse model exhibits a smooth variation of resistivity vertically at every VES site. For VES stations along a profile, a quasi-2D resistivity section can be constructed by concatenating the inverse models and use a contoured representation of the resistivity values. To improve the correlation of layers between one sites to the adjacent sounding sites, the number of VES data along the profile are augmented by using interpolation (Riss et al., 2010). The introduction of lateral continuity or smoothness after the inversion is somewhat arbitrary or artificial. However, satisfactory results have been obtained and relatively meaningful geological conclusions can be inferred (Grandis and Irawan, 2012; Grandis et al., 2013).

In order to employ more formal approach, we introduce a horizontal smoothness constraint by minimizing the resistivity variations of the same layer at adjacent sounding sites. In this perspective, layers' continuity in the resistivity section can be increased. We define the resistivity variation of an i-th layer at three consecutive VES sites around k-th site as:

$$H = (\log\rho_{i}^{k-1} - \log\rho_{i}^{k})^2 + (\log\rho_{i}^{k+1} - \log\rho_{i}^{k})^2 \qquad (3)$$

In both Equtions (2) and (3) the differences are calculated using the logarithmic of the resistivity to accomodate the large interval of resisitivity values. The modified Equation (1) incorporating both vertical and horizontal smoothness constraints is then expressed by:

$$P(R_j) = \exp(-E(\mathbf{m} \mid \rho_i = R_j) - \alpha V - \beta H) \qquad (4)$$

where α and β are weights for the vertical and horizontal smoothness constraints respectively. The values of α and β is determined by trial-and-error. However, after evaluating the order of magnitude of each term in Equation (4), α and β can be selected around 10 to 20.

In the application of only vertical smoothness constraint, the inversion of VES data from sites along a profile is done individually station by station without any order. For the application of both vertical and horizontal smoothness constraints, inversions of VES data must be performed sequentially, i.e. first, second, third sites and so forth. During individual inversion of VES data at one station, only a small number of iterations is performed in order not to overfit the data. Then, one complete update of models at all VES stations corresponds to one iteration. A large number of iterations is necessary to reach convergence and the inverse model is obtained by averaging 25% to 50% of models from last iterations.

INVERSION OF SYNTHETIC DATA

We tested the algorithm by inverting synthetic data. We use a 2D synthetic model representing a simple resistivity structure at shallow to intermediate depth of a typical geothermal system. The conductive layer (10 Ohm.m) with 500 meters constant thickness is embedded in a moderately resistive layer (100 Ohm.m) overlying a resistive (500 Ohm.m) basement. The depth of this layer varies and forms an asymmetrical anticline with a gentle increasing deepth to the left and to the right of the profile (Figure 1, top).

Along the profile crossing the model, 17 VES data were calculated by using the 1D forward modeling assuming independent stations. The maximum AB/2 is 1200 meters. Gaussian noise with 10% standard deviation of the theoretical data was added. The stations' spacing is 200 meters and the data were interpolated to obtain VES data at every 100 meters. The apparent resistivity pseudo-section is presented in Figure 1 (bottom).

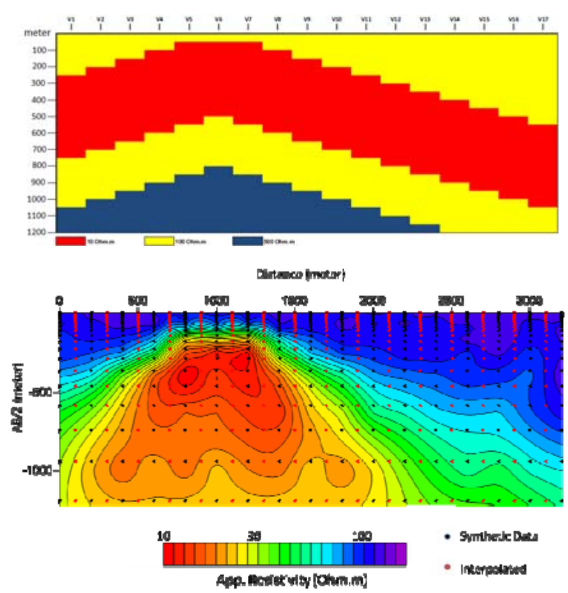

Figure 2. Synthetic model (top) and its associated apparent resistivity pseudo-section (bottom).

The result from inversion of the synthetic data applying both vertical and horizontal smoothness constraints is shown in Figure 3. For comparison, the previous result using only vertical smoothness constraint (Grandis et al., 2013) is also presented in the same figure. In general, it can be observed that the application of vertical and horizontal smoothness constraints lead to a better recovery of the 2D synthetic model. In this case, the optimum model was obtained with α lower than β, i.e. the horizontal smoothness dominates over the vertical smoothness. In both models, the thickness of the low resistivity layer appears under-estimated. Furthermore, the deeper flanks of the conductive layer are less pronounced due to decreasing resolution of the VES data with depth. Nevertheless, the resistive substratum that may represent the reservoir can still be identified.

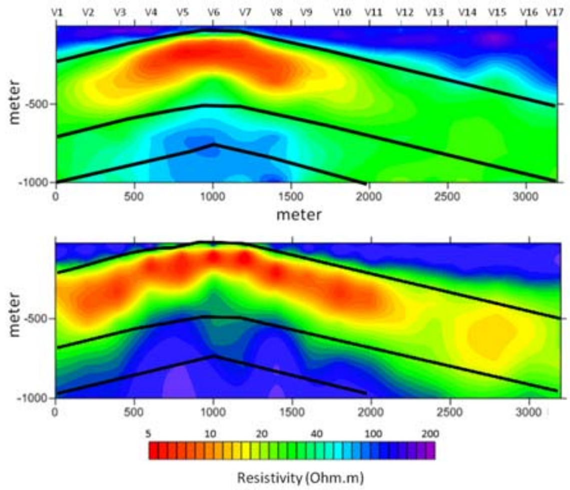

Figure 3. Inverse models from inversion by using vertical smoothness constraint only (top) and by adding horizontal smoothness constraint (bottom).

INVERSION OF FIELD DATA

The real data were acquired on a small part of a geothermal field in order to test the performance of both the geo-electrical method and the inversion algorithm. The field data consist of 17 VES points along a 4.5 km profile with station spacing of 200 to 300 meters (Figure 4). The profile crosses several wells, i.e. WWT-2, WWD, WWQ and MBD-2 from South to North. However, only well data from MBD-2 is available for comparison of inversion results.

The measured data up to AB/2 = 1500 meters were laterally interpolated by using Krigging technique (Riss et al., 2010) to obtain a more regular VES data at every 100 meters. Figure 5 shows the apparent resistivity pseudo-section. The data show clear transitions from moderately resistive superficial unit to a more conductive unit at depth. The resistive upper layers appear to be thicker to the South.

Similar inversion parameters as for inversion of the synthetic data were used. The model was limited up to 1000 meter depth in accordance with the maximum AB/2 which is only 1500 meters. As a rule of thumb, the investigation depth of VES data is approximately a third up to a half of the maximum AB/2. The inverse model presented as a quasi-2D resistivity section is shown in Figure 6. The conductive cap layers (less than 10 Ohm.m) are well recognized at shallow to moderate depths (600 m) which are typical attainable target for most geo-electrical survey for this purpose.

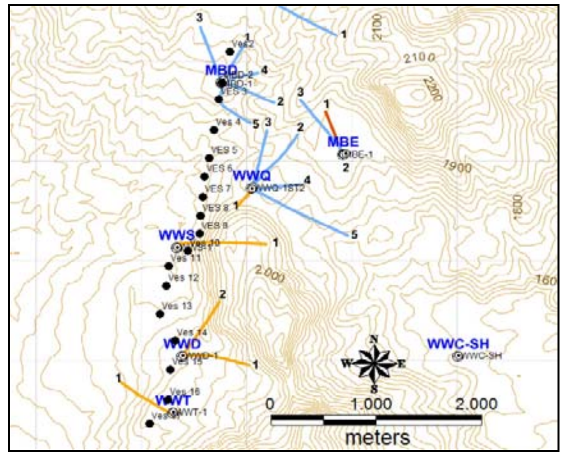

Figure 4. Map showing the distribution of VES stations at XX geothermal field.

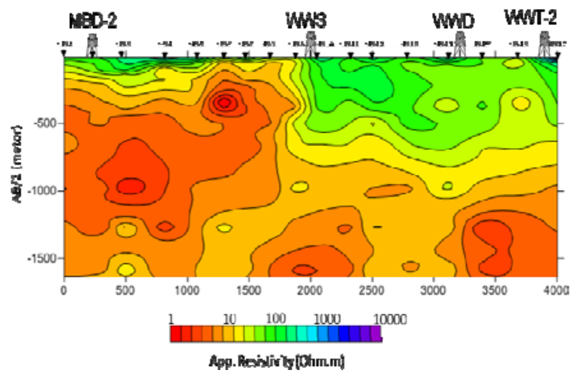

Figure 5. Plot of VES apparent resistivity data as pseudo-section.

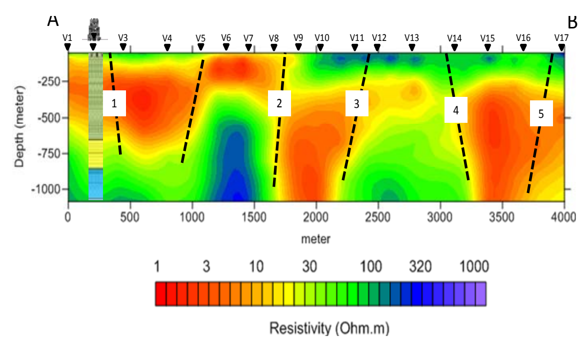

Figure 6. Quasi-2D resistivity section from inversion of the field data and its structural interpretation. The numbered structures are those identified from the geological data as faults and lineaments.

Inversion result for stations close to MBD-2 well data shows that the conductive cap layer can be correlated to Malabar Formation. The Malabar Formation consists of lavas, tuffs, and lahars derived from the Malabar volcanic center. Resistive layers (more than 100 Ohm.m) below the con-ductive cap rocks corresponds to Pangalengan Formation which constitutes the reservoir of the geothermal system in this area. The Pangalengan Formation consists predo-minantly of intercalated lahars and tuffs. This unit is further distinguished by a basal conglomerate that is overlain by interbedded sandstones, siltstones, and minor lignite beds.

The uneven thickness variation of the conductive layers necessites further investigation related to simplistic character of the 1D approximation for otherwise 2D or even 3D environment. However, it was informed that productive wells correlate with thicker conductive cap. The model in Figure 6 illustrates that the thicker conductive layers means deeper reservoir with presumably better production of steam. Furthermore, thickness variation and discontinuity of the conductive layers can be identified as geological structures present in the area. The surface extension of structures shown in the inverse model (Figure 6) are confirmed by geological data, i.e. interpretation of remote sensing images, aerial photography and supported by surface geology.

CONCLUSION

Inversion of geo-electrical VES data employing a guided random search algorithm performed well in obtaining 1D models for a series of VES data along a profile. Additional constraints were added favoring both vertical and horizontal smooth variations of resitivity. In most cases, lateral continuity of layers can be significantly improved and results in a more realistic quasi-2D model. The algorithm was tested to invert synthetic data associated with the relatively shallow part of a representative geothermal system. The inverse model is in a good agreement with known synthetic model.

The inversion of real data from a well-known geothermal field resulted in a quasi-2D resistivity model representative of the subsurface of the studied area. The survey area covered only a very small portion of the geothermal system that might influence our results. The conductive cap rocks are well resolved at shallow to moderate depths (600 meters) which are typical accessible depth for geo-electrical data. Uneven thickness variations of the conductive layers may reflect real structures as confirmed by geological data. However, they need further assessment whether they are effects of over-simplification of 2D or even 3D medium. The use of full 2D geo-electrical modeling in the inversion will be further investigated to obtain more realistic and more reliable resistivity image of the subsurface.

REFERENCES

Auken, E., Anders, V., Christiansen, Jacobsen, B.H., Foged, N., Sørensen, K.I., 2005, Piecewise 1D laterally constrained inversion of resistivity data, Geophysical Prospecting, 53, 497-506.

Dahlin, T., 1996, 2D resistivity surveying for environmental and engineering applications, First Break 14(7), 275-283.

Delgado, O.R., Shevnin, V., Ochoa-Valdez, J. and Ryjov, A., 2006, Geoelectrical characterization of a site with hydrocarbon contamination caused by pipeline leakage, Geofísica Internacional, 45, 63-72.

Ekinci, Y.L. and Demirci, A., 2008, A damped least-squares inversion program for the interpretation of Schlumberger sounding curves, Journal of Applied Sciences, 8, 4070-4078.

Grandis, H. and Irawan, D., 2012, Pemodelan inversi 1-D data VES konfigurasi Schlumberger menggunakan algoritma Markov chain Monte Carlo (MCMC), Proceedings 37th HAGI Annual Convention & Exhibition, Palembang.

Grandis, H., Irawan, D. and Sumintadireja, P., 2013, Shallow to moderate resistivity structure of a geothermal field from inversion of geo-electrical sounding data, Proceedings 2nd ITB Geothermal Workshop 2013, Bandung.

Loke, M.H., 2003, Tutorial: 2-D and 3-D electrical imaging survey, geotomo Software, Penang, Malaysia.

Meju, M.A and Montague, M., 1995, Basis for a flexible low-cost automated resistivity data acquisition and analysis system, Computer & Geosciences, 21(8), 993-999.

Riss, J., Fernandez-Martínez, J.L., Sirieix, C., Harmouzi, O., Marache, A. and Essahlaoui, A., 2010, A methodology for converting traditional vertical electrical soundings into 2D resistivity models: Application to the Saïss basin, Morocco, Geophysics, 76, B213-B224.

Sen, K.M. and Stoffa, P.L., 1995, Global Optimization Methods in Geophysical Inversion, Elsevier, New York.

Sharma, S.P. and Verma, S.K., 2011, Solutions of the inherent problem of the equivalence in direct current resistivity and electromagnetic methods through global optimization and joint inversion by successive refinement of model space, Geophysical Prospecting, 59, 760-776.

White, R.M.S., Collins, S. and Loke, M.H., 2003, Resistivity and IP arrays, optimised for data collection and inversion, Exploration Geophysics, 34, 229-232.