Removal of Topographic Effects in IP Method Complex Image Approach

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Summary
Using the method of complex image, the of topographic effect can be approximated based on the wave propagation patterns: surface to surface, surface to air and surface to subsurface. For a homogeneous medium with topography, it was shown that for a traverse over a hill a negative apparent resistivity anomaly is obtained while the transmitter is lying and fixed on the foothill and the receiver is moving along the traverse crossing the hill. For the same method, a traverse over a valley will result in a positive apparent resistivity anomaly. If the transmitter and the receiver are moving together at the same direction and keeping the separation distance between them constant an anomaly occurs only along the traverse where the source of anomaly is existing between the transmitter and the receiver. If the source of anomaly is an intersection between the horizontal plane and a sloping up plane, the shape of anomaly is similar to a wavelet. In this case the negative anomaly is associated with the confined current at the intersection and the positive anomaly is caused by the sparse current beyond the intersection. Using the method of complex images, the effects of topography is determinable. Thus using the method of image, the effect of topography is removable from the field data.

Key words:
electromagnetic coupling, mutual impedance, complex image, apparent resistivity, topographic effect, anomaly.

1. Introduction

Topographic effect in Induced Polarization method is a not yet resolved properly problem. Coggon [1] used finite element method to calculate the electromagnetic effect of a topography. He claimed that, for the dipole-dipole method, the nature of the topographic effects in apparent resistivity is not clear. Using computer program written by Rijo [2] (i.e., also using finite element method), Fox et. al. [3] conducted the study of the topographic effect in resistivity and IP Induced Polarization) methods. Based on this computer program they claimed that there is no IP anomaly caused by the topography. For EMC (Electromagnetic Coupling), however, Fox et. al. [3] claimed that the topographic effect is important for slope angles of 10 degrees or more and the slope length of one dipole length or greater. There are many other solutions that had been presented, however the users have not satisfied with the result.

Commonly, determination of topographic effect in dipole-dipole method is by assuming that the transmitter and the receiver are lying on the same horizontal plane (i.e., Coggon [1], Rijo[2] and Fox et. al. [3]). This approach is valid only if the different altitude between the transmitter and the receiver is small in comparison to their separation distance. Furthermore, although the vertical displacement of the topographic low or high is negligible in comparison to the infinite extend of the medium, the orientation of the transmitter and the receiver can be non-negligible. It was shown by Sinha [4] that misorientation between the transmitter and the receiver can lead to an erroneous result. Based on this argument, this approach is not valid around an intersection between two planes (i.e., representing the topographic). In the case of topographic low or high, the interface is no longer horizontal. Therefore, we should take into account the effect of difference altitude between the transmitter and the receiver in calculating the radiated electric field. If position of the receiver is topographically higher than the plane on which the transmitter exist then the medium between the receiver and the plane on which the transmitter exist is assumed to be the air. On the other hand, if position of the receiver is topographically lower the plane on which the transmitter exist then the medium between the receiver and the plane on which the transmitter exist is assumed to be the earth.
Based on the radiation pattern of the Hertzian dipole, if the receiver is higher than the transmitter than the transmitted electric field is better approach with the radiation field from surface to air propagation. On the other hand, if the receiver is lower than the transmitter than the transmitted electric field is better approach with the radiation field from surface to subsurface propagation. If the transmitter and the receiver are lying on the same horizontal plane, the transmitted electric field is calculated based on surface to surface propagation. It is understood that using integral method calculation of such fields are difficult (Sinha [4]). By applying complex image theory, Bannister [5] derived the electric field equation for surface to surface, surface to air and surface to subsurface radiation pattern. This method was successfully applied in calculating the total electromagnetic field.

Manuscript received March 5, 2011
Manuscript revised March 20, 2011

2. Determination of Topographic Effect

Theoretically, if a transmitter is set on a horizontal plane, in comparison to the current in the horizontal plane, the current is confined in the topographically low medium, and it is diverged in the topographically high medium. In the other words, in comparison to its normal value, current density is higher in the topographically low medium than in the topographically high medium. For a traverse over such condition, the results obtained should be positive conductivity anomaly in the topographically low area, and negative conductivity anomaly in the topographically high area. If the sloping up angle and the sloping down angle are the same in magnitude, distance between the source and the receiver that is lying on the sloping up plane and that between the source and the receiver that is lying on the sloping down plane are the same. Path of the wave propagation, however, are different. In the first case, the transmission is surface to air propagation, and in the second case the transmission surface to subsurface propagation. Based on the complex image theory, if the transmitter is lying on the horizontal plane, distance between the image and the receiver that is lying on the sloping-down plane is shorter than that between the image and the receiver that is lying on the sloping-up plane. The contribution of image, therefore, is higher for the surface to subsurface propagation than for the surface to air propagation. The effect of higher or lower contribution from image is the same as the effect of high density or low density of current. Solving the topographic effect by using the method of image, therefore, is appropriate. Note also that, since the separation distance between the transmitter and the receiver can be much smaller than distance between the receiver and the image, the contribution from image can be negligible. Using the complex image approach general view of the orientation of the transmitter and the receiver, and the associated electric field components generated at the receiver are shown in Fig. 1.
From Fig. 1, the dependence of the total electric field (i.e., parallel with the receiver) on the orientation of the transmitter and the receiver, and the difference elevation between the transmitter and the receiver can be written as:

$$E_{//} = E_x Cos\xi Cos\theta + E_y Sin\xi Cos\theta + E_z Sin\theta \quad (1)$$

where Ex, Ey and Ez are the x, y and z components of the electric field at the receiver. Note that Eq. 1 is the general form of the total electric field component that is parallel with the transmitter. The electric field detected by the receiver is the total electric field generated by the transmitter AB and its image A‘B’, which depends on the difference altitude of the transmitter (AB) and the receiver (MN).
For all three orientations of the transmitter and the receiver considered (i.e., the surface-to-surface (Fig. 2), surface-to-air (Fig. 3) and surface-to-subsurface (Fig. 4) propagations), and by referring to Fig. 1 and Eq. 1, we can deduce that for the surface-to-surface propagation we have =0, z=0 and =0. Therefore, we are allowed to write (see Fig. 2):

$$E_{//} = E_x \quad (2)$$

Note that in this case R=R0, R0= , =x, Ri=R0i and

$R_{0i} = \sqrt{x^2 + d^2}$ Note also that to distinguish among the different types of propagation the subscripts 0, 1 and 2 are assigned for surface-to-surface propagation, surface-to-air propagation and surface-to-subsurface propagation respectively.

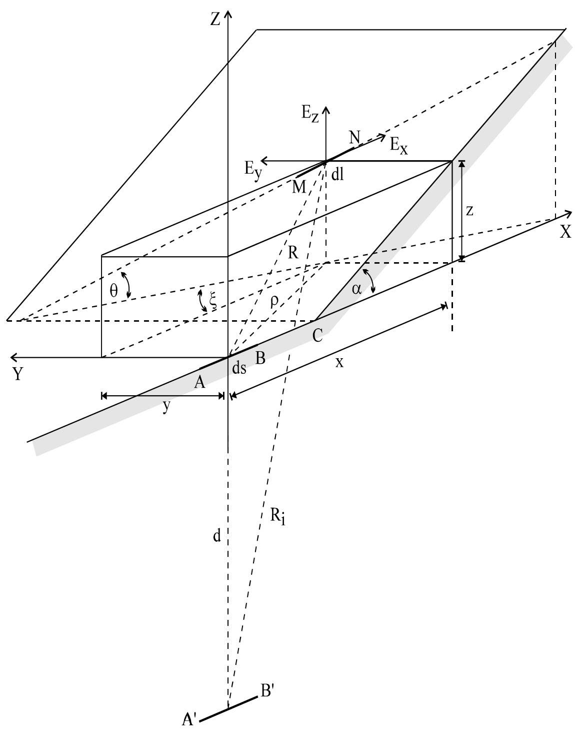

Fig. 1 General view of the orientation of transmitter AB and receiver MN. AB is on the horizontal plane and MN is on the sloping plane. The angle between the two planes is (180-) degrees. Note that the origin of coordinate system is at the center of the AB. Note also that A’B’ is the generated image.

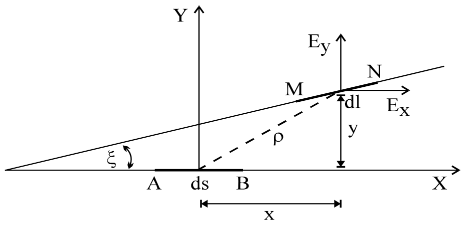

Fig. 2 Plan view of the surface-to-surface propagation.

If the receiver lies on a plane that is topographically higher than the plane on which the transmitter is located (i.e., the surface-to-air propagation), then we have >0 and >0. The total electric field component that is parallel with the receiver, therefore, can be written in the form of (see Fig. 3):

$$E_{//} = E_x Cos\alpha + E_z Sin\alpha \tag{3}$$

Note that in this case R=R1, =x, $R_1 = \sqrt{x^2 + z^2}$, Ri=R1i and $R_{1i} = \sqrt{x^2 + (d+z)^2}$.

If the receiver lies on the plane that is topographically lower than the plane on which the transmitter is lied (i.e., the surface-to-subsurface propagation) then we have <0 and <0. The electric field component parallel with the direction of the receiver, therefore, can be given as (see Fig. 4):

$$E_{//} = E_x Cos\alpha - E_z Sin\alpha \tag{4}$$

Note that in this case R=R2, =x, $R_2 = \sqrt{x^2 + z^2}$, Ri=R2i and $R_{2i} = \sqrt{x^2 + (d-z)^2}$. Note also that in addition to the propagation patterns, the main difference between the sloping-up and the sloping-down media is distance between the image and the receiver.

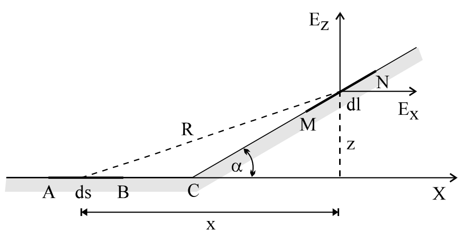

Fig. 3 Crossectional view of the surface-to-air propagation.

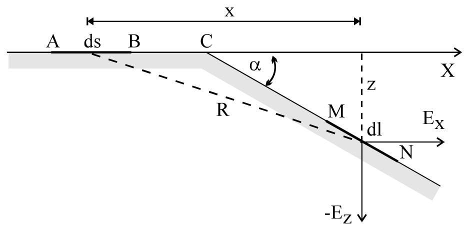

Fig. 4 Crossectional view of surface-to-subsurface propagation.

In practice, the transmitter sometimes crosses the intersection between the horizontal and sloping planes. In this case, since the transmitter is no longer horizontal, the propagation patterns become either surface-to-surface and surface-to-air or surface-to-surface and surface-to-subsurface. In the other words, in this case the transmitter consists of two segments. If the point at which the transmitter is crossing the intersection between the two planes is assumed to be point C, the two segments of the transmitter are AC and CB. Since the potential is a scalar quantity, the total potential detected by the receiver is the algebraic sum of the potential generated by the two segments. The same consideration is taken for a receiver that is crossing the intersection between the two planes.

The mutual impedance between the transmitter and the receiver is the ratio of the total potential detected by the receiver and the current introduced into the ground through the transmitter, and it can be written as (Sitepu [6]):

$$Z_m = \frac{e^{\gamma_1 z}}{4\pi j\varepsilon_0\omega}\int_M^N\int_A^B\left\{\left(-\gamma_0^2\prod_x + \frac{\partial^2}{\partial x^2}\prod_x + \frac{\partial^2}{\partial x\partial z}\prod_z\right)Cos\alpha - \left(-\gamma_0^2\prod_z + \frac{\partial^2}{\partial z\partial x}\prod_x + \frac{\partial^2}{\partial z^2}\prod_z\right)Sin\alpha\right\}dsdl \tag{5}$$

where $\gamma_0 = \mu_0\varepsilon_0\omega^2$ and the x and z components of the Hertz vector potential are the same as those given in the surface-to-surface propagation. Note that in this case $\rho = x$, $R_0 = \sqrt{x^2 + z^2}$ and $R_i = \sqrt{x^2 + (d-z)^2}$ for the dipole-dipole array.

It is obvious that the x and z components of the electric field depend on double differentiation of the x and z components of the Hertz vector potential. Since the Hertz vector potential generated by the source and that generated by the image are in the same form, for each image and source can be written as (Sitepu and Susilawati [7]):

$\rho_i = \sqrt{x_i^2 + y^2}$ and $R_i = \sqrt{\rho_i^2 + (z + d_i)^2}$

$$\prod_{x_i} = \frac{e^{-\gamma_0 R_i}}{R_i} \quad \text{and} \quad \prod_{z_i} = \frac{x_i(z+d_i)}{\rho_i^2}\frac{e^{-\gamma_0 R_i}}{R_i} \qquad (6)$$

The apparent resistivity, therefore, can be obtained by using:

$$\rho_a = |Z_m| \pi L m (m^2 - 1) \qquad (7)$$

where L is one dipole length, m is the separation distance between the transmitter and the receiver in term of L (i.e. m=L, 2L, 3L,…..). Note that except for 0 which is the wave propagation constant in air, each parameter with subscript zero is the parameter that is associated with the transmitter. For example $d_0 = 0$ is the depth of transmitter from the surface, x_0 is the horizontal distance between the transmitter and the receiver and $\prod_{x_0}$ and $\prod_{z_0}$ are the x and z components of the Hertz vector potential generated by the transmitter.

From the above equations it is clear that the mutual impedance between the transmitter and the receiver depends on the difference altitude between the transmitter and the receiver. Since the difference altitude between the transmitter and the receiver is caused by the topography therefore the mutual impedance between the transmitter and the receiver also depends on the topography.

It is understood that topographic effect does not directly effet the apparent resistivity. The mutual impedance between the transmitter and the receiver, however, is influenced by the topographic effect. Since the mutual impedance already contains the topographic effet, the EMC and topographic effects, therefore, should be removable simultaneously by using Eq. 7.

3. Homogeneous Medium with Topography

Since we are interested in observing the effect of topography, for simplicity the medium is considered as homogeneous. In practice, the sloping angle seldom exceeds 45 degrees. The variation of slope angle, therefore, is chosen as 15, 30 and 45 degrees. Note that in this case the intersection between the horizontal plane and the sloping plane is assumed as the zero position (i.e., the reference point). The same as that given previously, the range of traverse distance is chosen as -7L to 7L, with the step size of 1L. Note also that unless otherwise stated, the characteristics of the medium are the same as those given previously, the frequency is 3 Hz and the true resistivity is 100 m.

3.1. Sloping Up and Sloping Down Topographies

It was shown in the previous section that basically the result obtained from a traverse over a sloping down topography is the same as that obtained from a traverse over a sloping up topography. The only difference is the anomaly caused by the sloping down topography is the opposite of that caused by the sloping up topography. Due to this reason the model presented involve only the sloping up topography. The slope angle is varied from 15 to 45 degrees, with the step size of 15 degrees. The minimum slope angle is chosen to be in agreement with the minimum angle suggested by Fox et. al. [3].

The intersection is selected as the reference point (i.e., zero position). The traverse is made from a negative distance to a positive one, with the transmitter following the receiver at a constant separation distance m. Since the shape of the anomaly is also m distance dependence, for the selected range of slope angle, we have chosen two values of m distance: 2 and 6. Note that n spacing in the pseudosection plot is the same as (m-1) distance in the 2D plot presented. In this case, the selected length of dipole is 50 meters. Plots of apparent resistivity as a function of m distance is given in Fig. 5 and Fig. 6.

From Fig. 5, the anomaly decreases for decreasing sloping angle. In this case the current density around the intersection is higher at a higher sloping angle. Thus this result agrees with the theoretical result. For the sloping up topography, the current density around the intersection is higher than normal, thus it appears as a low resistivity medium. As a result, it appears as a negative anomaly. Once the current has passed the intersection, in comparison to the normal current density (i.e., if it was no topography), the current density decreases for increasing distance from the intersection. A more sparse current is characterized as a higher resistivity. As a result, a positive anomaly is presented. A traverse crossing an intersection between a horizontal plane and a sloping up plane, therefore, results in negative and positive anomalies. The anomaly is more spreading out for a longer separation distance. In this case, a longer m distance needs more steps to completely cross the intersection, thus more spread the anomaly becomes. It is obvious that the anomaly is obtained if the intersection is existing between the receiver and the transmitter. Once there is no obstacle between the transmitter and the receiver there is no anomaly detected. This result is in agreement with the argument previously given: a traverse over a hill will give a positive resistivity anomaly if the transmitter is made fixed. On the other hand, if the transmitter and the receiver are moving together the anomaly is presented only in the range while the intersection is in between the transmitter and the receiver. It is obvious that the results obtained are consistent throughout the examples.Since the graphic in

Fig. 5 is the opposite of the graphic in Fig. 6, explanation for Fig. 6 should be clear from the discussion given for Fig. 5.

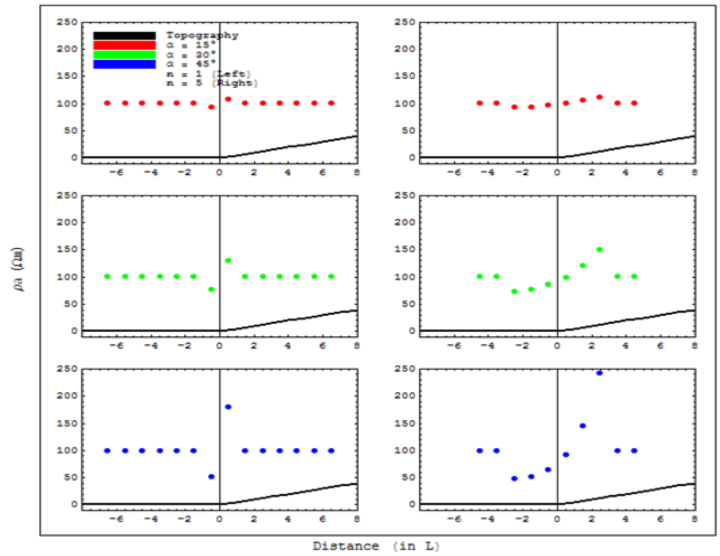

Fig. 5 Plots of ρa as a function of traverse distance for ρ=100 Ωm, f=3 Hz and L=50 meters at slope angles of 45, 30 and 15 degrees.

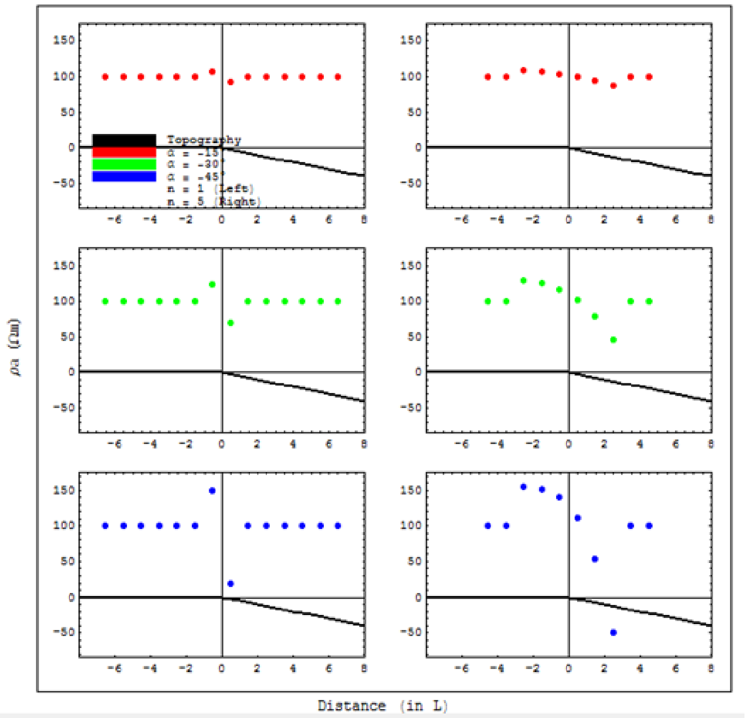

Fig. 6 Plots of ρa as a function of traverse distance for ρ=100 Ωm, f=3 Hz and L=50 meters at slope angles of 45, 30 and 15 degrees.

3.2. Hill and Valley Like Topography

To conclude the investigation, let us see the apparent resistivity anomaly of a traverse over a hill and a valley. The medium is assumed to extend infinitely both laterally and vertically downward. Distance is measured in terms of dipole length. The reference point is chosen to be the center of the top of the hill or valley, with the x, y and z directions are following the normal Cartesian coordinate system. The traverse is conducted from the negative distance to positive distance. The slope angle of the hill is assumed to be 30 degrees, and the slope angles are the same for sloping up and sloping down planes. As usual, the medium is assumed to be homogeneous with the resistivity of 100 Ωm.

Measurement by using dipole-dipole array is conducted at the frequency of 3 Hz. Dipole length is chosen as 50 meters. Since the shape of the anomaly is highly affected by the separation distance between the transmitter and the receiver, we have selected two m values: 2 and 4. Plots of the apparent resistivity as a function of traverse distance is given in Fig. 7.

From Fig. 7, it is obvious that the sloping up topography gives the positive anomaly higher than the negative anomaly. The reversal situation is encountered in sloping down topography. The main reason to this occurrences is the dominant effect of either surface-to-air propagation or the surface-to-subsurface propagation. This is obvious in Fig. 7 where the effect of a traverse from a horizontal plane to a sloping up is the same as the effect of a traverse from sloping down plane to horizontal plane. The same effect is also found from a traverse from sloping up plane to horizontal plane and a traverse from horizontal plane to a sloping down plane. In agreement with one would have expected, the anomaly is fluctuated about the true resistivity value.

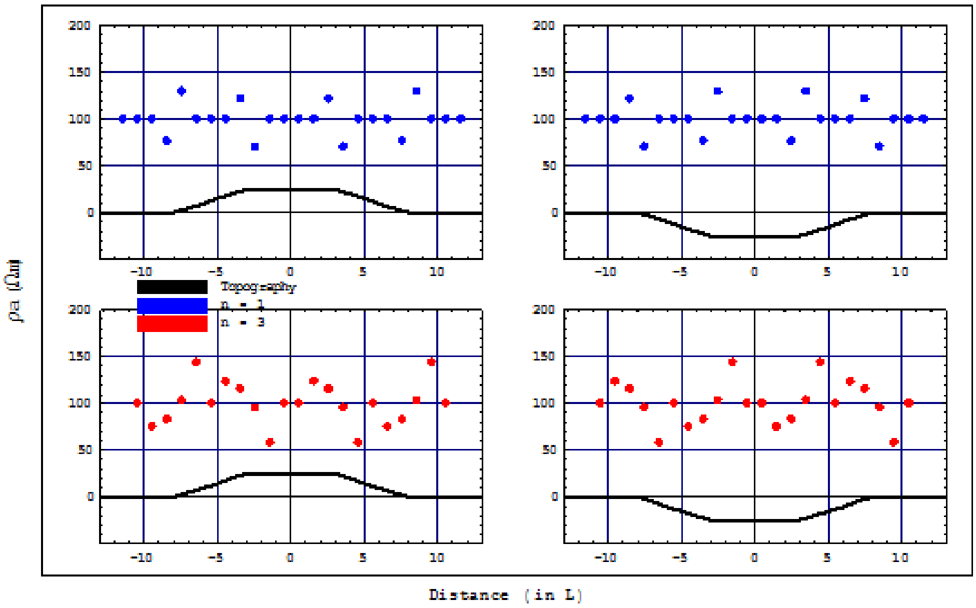

Fig. 7 Plots of ρa as a function of traverse distance.. Note that we are assuming ρ=100 Ωm, f=3 Hz and L=50 meters, and the slope angle is 30 degrees.

4. Removal of EM Coupling and Topographic Effects

Data were collected in the field location in Indonesia. For security reason, the exact location of the field is withhold. The instrument used in the field was the Geoservices IP set. The transmitter is Phoenix IPT1 (3 KVA) and the receiver is Phoenix IPV1. The instrument functions for frequency domain method with the operating frequencies of 0.25 Hz and 2.5 Hz. Data were collected on May 31, 1995. Prior to taking IP data, topography data were collected for every 10 meter. The line was chosen to be North-South, at the eastern part of the prospect. Plot of the topography along the line is given in Fig. 8.

Data were collected by using dipole-dipole array, with the dipole length of 50 meters. In many cases, the reference point is chosen at the center of the traverse (i.e., the number of data points prior to and after the reference point are the same, and the distance is measured in term of dipole length). For example, in Fig. 8, the reference point can be assumed as the point at the distance 2850 meters. In this case, however, the traverse distance is measured in terms of distance from the origin (i.e., the starting point of the traverse is not the same as the origin).

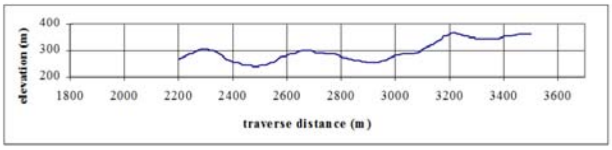

Fig. 8 Plot of the topography along the traverse.

Since the shape of apparent resistivity anomaly also depends on the n value, fitting the apparent resistivity obtained from field and that obtained from the model is carried out for every n value. Once we get the best fit between the field data and data obtained from the model, we can claim that the true resistivity of the host medium is equal to the true resistivity obtained from the model, and the anomaly existed is that caused by the electromagnetic coupling and topography. The best fit of the plots of apparent resistivity obtained from the field and that obtained from the model is given in Fig. 9. Based on the model, the estimated resistivity of the host medium is 33 Ωm. It is obvious that the effects of electromagnetic coupling and topography obtained from the model fit some of the anomalies found in the field data. The most interesting evidence is the fact that the agreement between the results obtained from the model and those obtained from the field is true for all values of n. This suggests that the difference in magnitude between the anomaly in the field data and that in the data obtained from the model is most likely caused by the prospect.

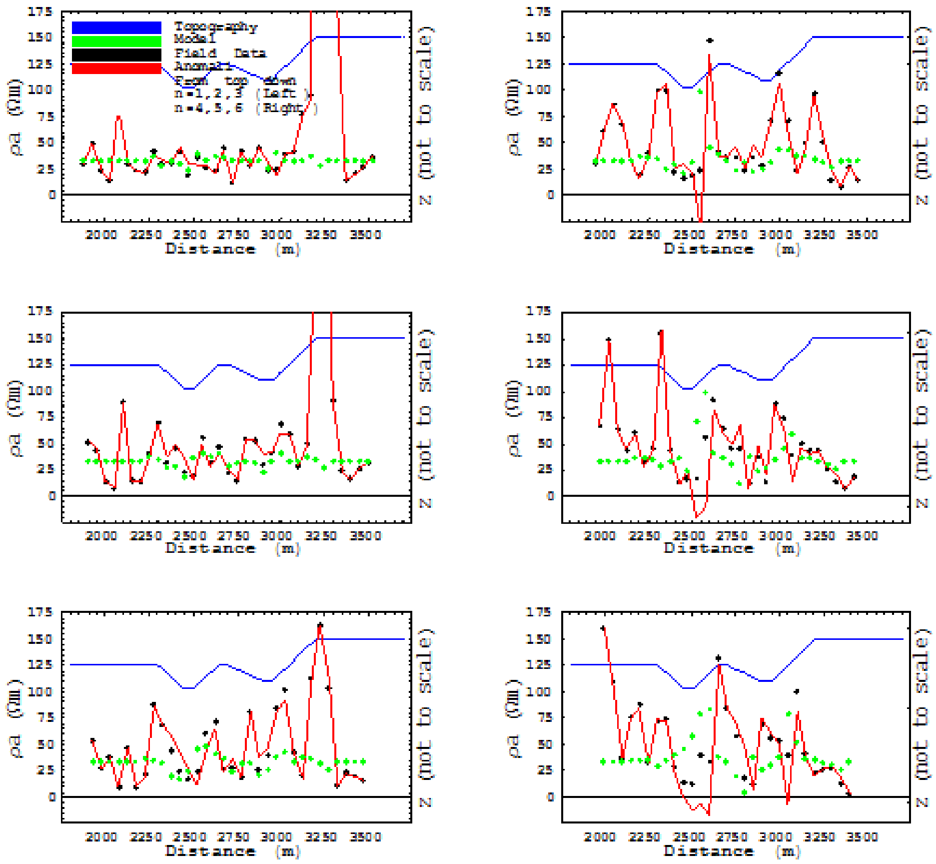

Fig. 9 Plots of apparent resistivity as a function of traverse distance for n=1 to n=6. Note that the slope angless are approximately 22 degrees, 22 degrees, 11 degrees and 24 degrees (from left to right), and dipole length is 50 m.

Pseudosection plot of the data gathered from the field is also presented. Fig. 10 is the contour plot of the data gathered from the field prior to removal of electromagnetic coupling and topographic effects. The legend shows the range of apparent resistivity of the data in Ωm.

Based on the model, resistivity of the host medium is 33 Ωm. By removing the effects of electromagnetic coupling and topography from the field data, and then by removing the effect of homogeneous host medium then the remaining result is the anomaly caused by the prospect. This result is presented in Fig. 11. From Fig. 11 it is clear that the apparent resistivity anomaly caused by the prospect is much more obvious in comparison to the result given in Fig. 10.

By moving transmitter and receiver at a constant separation distance, and if the medium is homogeneous, a traverse over a sloping up or sloping down topography will give a difference apparent resistivity anomaly. Since the medium is assumed homogeneous, the disturbance of the equipotential is caused by the intersection between the horizontal plane and the sloping plane. In this case if there is no obstacle between the transmitter and the receiver there is no difference between the apparent resistivity obtained and the true resistivity value. Therefore there is no anomaly. However, since both the transmitter and the receiver are moving together the intersection between the horizontal plane and the sloping plane is existing between the transmitter and the receiver. During the existence of the intersection between the transmitter and the receiver, the receiver detected a disturbed equipotential. As a result the apparent resistivity presented is not the same as the true resistivity value. Thus, there is anomaly. Once the intersection is no longer in between the transmitter and the receiver the receiver detects the undisturbed equipotential lines. As a result the apparent resistivity presented is the same as the true resistivity value. This result is also evidence in the result of the model presented.

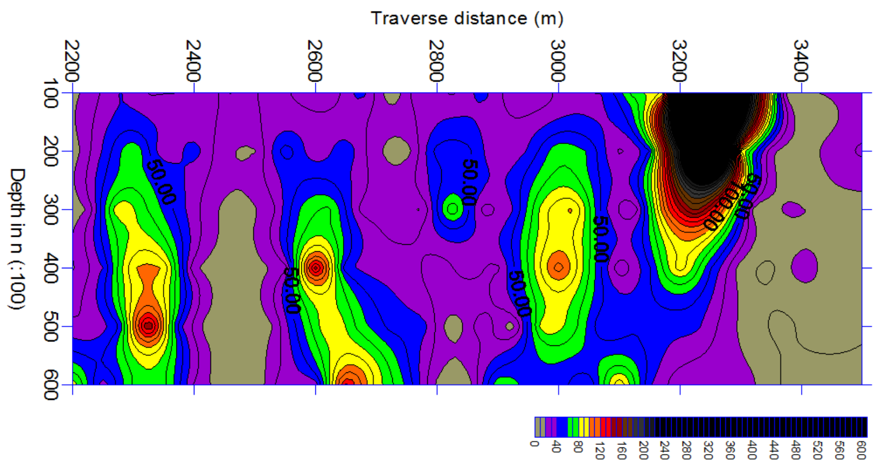

Fig. 10 Plot of apparent resistivity prior to removal of electromagnetic coupling and topographic effects from the field data.

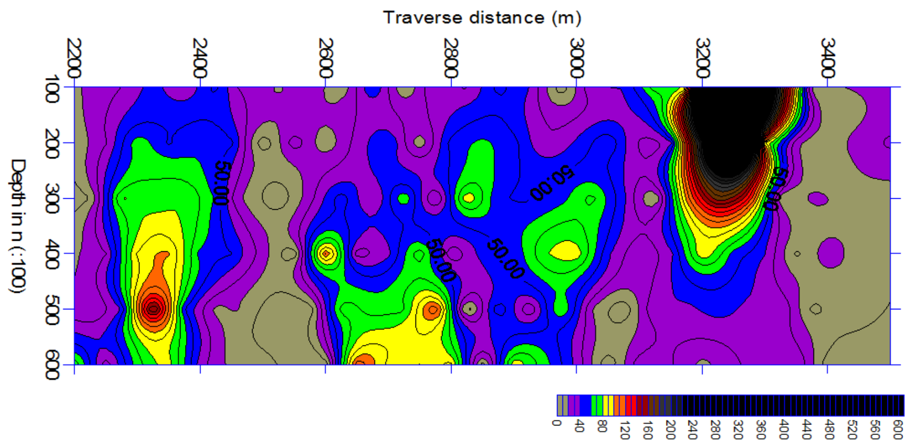

Fig. 11 Plot of apparent resistivity anomaly after removal of electromagnetic coupling and topographic effects from the field data.

From the model, the best fit between the plots obtained from the models and those obtained from the field data is found at the true resistivity of the homogeneous medium of 33 Ωm. This indicates that assuming the host medium is homogeneous, the true resistivity of the homogeneous medium is 33 Ωm. For this value of resistivity, the shape of the anomalies caused by the topography (i.e., obtained from the models) are the same as the suspected anomalies caused by topography in the field data. The agreement between the results obtained from the model and those obtained from the field is true for all values of separation distance between the transmitter and the receiver (i.e., n=1 to n=6). This suggests that the difference in magnitude between the anomaly in the field data and that in the data obtained from the model is most likely caused by the prospect. This is in agreement with the fact that the field data were collected from an important line acquired in Indonesia.

Based on the above discussion, there is no doubt that the method of image is satisfactory to be used in calculating the mutual impedance between the transmitter and the receiver. Using the dipole-dipole array, the apparent resistivity anomaly, caused by the change of the mutual impedance as a result of the presence of topography, is detectable.

The highly agreement between the plot obtained from the model and that obtained from the field suggests that the method of images is applicable to removing the topographic effects from the field data. The result presented in Fig. 11 support the argument that the method of image is satisfactory to be used to remove the effects of electromagnetic coupling and topography from the field data gathered using dipole-dipole method.

5. Conclusion and Suggestion

Using a model to depict a topographic encountered along a traverse line in the field, the results obtained agree highly with those obtained from the field. The agreement between the results obtained from the model and those obtained from the field is true for all values of the separation distance between the transmitter and the receiver (i.e., for n=1 to n=6). From these, one can conclude that applying the method of images the topographic and electromagnetic coupling effects can be removed simultaneously from the field data gathered using dipole-dipole method.

In addition to the quasistatic field restriction, the method of image is subject to two major limitations: the distance of interest is very small in comparison to the wavelength in the air, and the distance between the image and the observation point on the surface is greater than the skin depth. Since the method of images depends on orientation and elevation difference between the transmitter and the receiver, the presence of a topography is detectable only if the transmitter and the receiver are difference in elevation.

Acknowledgments

Authors would like to acknowledge that part of the Research was Funded by the DGHE of Indonesia, under Hibah Bersaing Researc Grant. Support from USU is also greatly appreciated.

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