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Efficacy of electrode arrays in resistivity prospecting using physical modelling

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ABSTRACT

Physical Model experimentation using resistivity profiling over metallic sheet-like target in different orientations has been carried out with different electrode configurations viz., Two-electrode, Three-electrode, Wenner and Dipole-Dipole with an objective to find out the relative merits and demerits of the arrays and to study the efficacy of one electrode configuration over the other. We have carried out experimentation in two ways viz., (i) the target depth (d) is fixed at a particular level and profiles are run with different arrays as mentioned above by changing the array spacings (L) for that particular depth. For this, the conducting target is submerged in the host medium water, in vertical position ($\theta=90°$) contained in the model tank and resistivity response characteristics are recorded for all arrays and their spacings in a systematic and sequential way and (ii) the same target is kept in different orientation i.e., in horizontal direction ($\theta=0°$) and its depths (d) are changed for a particular array spacing (L) of the array so that an in-depth understanding of the theme can be had i.e., variation of the anomaly with depth, with orientation, with array spacing and with type of the array .

An overall study on efficacy of the electrode arrays over both the targets indicated that the profiles are broadened over horizontal conducting sheet compared to those over a vertical sheet. The reason is that, the area of exposure to the measuring system is very large in comparison with the exposed area of vertical sheet.

Over the vertical conducting sheet, the Wenner apparent resistivity profiles show a W-shaped pattern whereas the profiles show a low only over the horizontal sheet. The other result that emerged out of the comparison of the different electrode arrays is that the two-electrode array gives the simplest and largest anomalies with the small electrode spacings for conducting metallic target. This array gives the best response with regard to amplitude and shape of anomaly. But placing the infinity electrodes puts a practical problem. Finally, Dipole -Dipole array is the next alternative as its response is symmetrical over a vertical sheet, better in shape and amplitude. But the Dipole-Dipole array demands large transmitting source power.

INTRODUCTION

Physical modeling in resistivity is to simulate the ground structure in the laboratory by scaling down the dimensions of the structure appropriately, keeping the same resistivity contrast as in the field and yet reproducing the same filed response. Physical model studies can be carried out with four electrode set-up keeping the target physically in the host medium of the model tank and measuring the responses at different transition parameters (Apparao. et al 1979, Apparao and Roy 1971, Apparao et al 1978, Mallick 1969, Saydam and Duckworth 1978, Apparao et al 1997). Physical model studies using multi electrodes are also in use to assist the interpretation of high resolution resistivity imaging data (Rekapalli et al, 2013). Excellent work has been carried out in scale model studies over different types of conducting targets (Apparao et al 1997) and resistive targets (Sarma et al 2001). Physical modeling is useful when the geometry of the problem is such that a theoretical solution of the potential is difficult. Even when a theoretical solution is available it may not be explicit and computations in many cases are not easy. Where rigorous analytical solution for a given ground structure does not exist, one can go for a numerical

modeling using finite different approximation. But, the later has got its own limitations. Even after the numerical modeling is carried out, it is essential to verify the results by physical modeling. Simulation in resistivity is based on the following principle.

Let us assume a simple ground structure consisting of a two-dimensional dyke of resistivity ρ_2 buried in an otherwise homogeneous medium of resistivity ρ_1 at a depth 'd' below the ground surface. The dyke is of thickness't' and of depth extent 'w'. The apparent resistivity ρ_a that is measured on the surface with an electrode array is a function of ρ_1, ρ_2, t, w and the array spacing 'a'. This is expressed as:

$$\rho_a = F\ (\rho_1, \rho_2, d, t, w, a)$$

if ρ_a and ρ_2, are expressed in terms of ρ_1 and d, w and a are expressed in terms of t, then the eq. can be written as:

$$\rho_a / \rho_1 = F_1\ (\rho_2/ \rho_1, d/t, w/t, a/t)$$

If the constituents of the function F_1 remain in the laboratory the same as in the given ground structure, then

$$(\rho_a/ \rho_1)_{lab} = (\rho_a/ \rho_1)_{field}$$

Modeling in resistivity is purely geometric; that is the scaling factor relates only to the linear dimensions of the target and the electrode array. The resistivity values and/or their ratios are not scaled. They retain the same value in the model as in the prototype.

A comparison of the relative performances of the different electrode arrays, at least the most widely used ones, seems to be most appropriate on the basis of the work done by others so far. Apparao and Roy (1971, 1973) have shown by model and field studies that the simplest two-electrode array is, by far, superior to the other electrode arrays – Wenner, Schlumberger and even focused systems like Unipole, modified Unipole- in magnitude and shape of anomaly, depth of detection, cost of operation as far as resistivity profiling over conducting vein-shaped target is concerned. Coggon (1973) compared the performances of the arrays- gradient, pole-dipole and dipole-dipole – and found that the dipole array gives the largest anomaly and is strongly influenced by overburden irregularities. Saydam and Duckworth (1978) found, on the contrary, that the pole-dipole array gave the highest apparent resistivity anomaly over a sheet-target while the pole-pole (two-electrode) array is the second best. In view of the conflicting results reported by the different workers, the authors felt necessary to study systematically by physical modeling the relative performances of the different arrays that are most widely used in mineral prospecting-Wenner, Two-electrode, Three-electrode and Dipole-dipole. The Schlumberger and half-Schlumberger arrays could not be tried in the laboratory for various reasons. However, it must be admitted that (i) the nature of the anomaly with Schlumberger is akin to that with Wenner and (ii) the three-electrode anomaly is similar in shape with that of half-Schlumberger though not in amplitude.

MODEL EXPERIMENTATION

For conducting the experiments, we have used for the present purpose, an infinitely conducting target like aluminium sheet of dimensions 110x10x1 cm. The aluminium sheet was placed in vertical direction initially to start with and different configurations like Wenner, Two-electrode, Three-electrode and Dipole-Dipole are used with an objective to find out the relative merits and demerits of the arrays and to study the efficiency of one electrode configuration over the other. The same exercise is repeated by keeping the target in horizontal position also so that an in-depth, understanding over the proposed theme is made. The depth to the target'd' is fixed at 1t and is the same for all the arrays, where 't' is the thickness of the target which is 1cm and this is taken as one unit for sheet- like targets. All the other parameters are expressed in terms of't' only. It may be noted that'd' perpendicular distance from top of the water to the target. The model tank was filled with tap Water which acts as host medium. The model tank used here is made up of wood and its interior was lined with transparent cellophane, which has the dimensions of length=200 cm, breadth=120 cm; depth=100 cm as shown in figure 1. The model tank consists of a trolley on the top of the tank, to which a system is connected to place the current as well as potential electrodes. The system has a scale to place these electrodes for different spacings. The trolley is made up of ebonite. This trolley is made to move on an ebonite rod, which has scale on it for taking proper measurements. The tank was filled with tap water ,which acted as the host medium. In the middle of the tank the target is placed. Physical

Model Experimentation has been carried out in the National Geophysical Research Institute, Hyderabad. Model tank setup with Wenner four electrode configuration is shown in figure 1.

Once after the requisite set up is fixed, the system check-up has been carried out. The apparent resistivity values are measured for different arrays with different electrode spacings before starting the experiment to make sure that the apparent resistivity measured by smallest and largest spacing of the electrode array are by and large the same. This exercise was carried out to check –up the tank wall effects. It is noticed that the average apparent resistivity value measured without the target in the tank with the smallest and largest electrode spacing is 8.5±0.3Ωm. Concurrently, the resistivity measured with the conductivity cell was also found to be 8.5±0.2Ωm, which is closely in agreement with the values measured with different electrode arrays in the model tank. Since the resistivities measured with smallest and largest spacings of an electrode array are, by and large, the same, it can be concluded that there are no serious tank wall effects on the resistivity measurements. Again, since the apparent resistivities are normalized with the resistivity of the host medium that is obtained far away from the target, the error in ρ_a/ρ_1 , due to wall effects, if any, (rarely) is also further minimized .The schedule of the model experimentation is given in the Table 1. All the model experiments are carried out at an operating frequency of 1000 Hz for the present studies, as this frequency is devoid of surface polarization effects (please refer Guptasarma,1983 for the details on this concept). While stain less steel electrodes are used for current transmission, silver-silver chloride electrodes are used as potential electrodes. The electrode set-up is kept in the model tank for carrying out the measurements. The apparatus used for measurements is a complex impedance measuring system (Guptasarma et al., 1981) with facility for wide band current excitation (0.001Hz to 10 KHz). The current sent into the Model tank did not exceed 300μA at any time.

The target model that is used for comparison of the electrode arrays is a two-dimensional metallic aluminium sheet of thickness 1.0 cm, depth extent 10 cm and of length 110 cm. It has been chosen because it is the simplest model to be thought of and further it suffices the purpose of comparison of

Figure 1. Model Tank setup with Wenner configuration (The horizontal sheet submerged in the Host medium (Water) is also seen in the above figure).

Table – 1.

Array	Array Spacing (L)	Vertical Aluminium Sheet	Horizontal Aluminium Sheet
Two-electrode	1t,2t,3t,4t,5t,6t	Depth(d)=1.0t	Depth (d) =0.5t,0.75t,1t,2t,3t,4t
Three-electrode	2t,4t,6t,8t,10t,12t		
Wenner	3t,6t,9t,12t,15t,18t		
Dipole-dipole (β-Wenner)	3t,6t,9t,12t,15t,18t (n=1)		

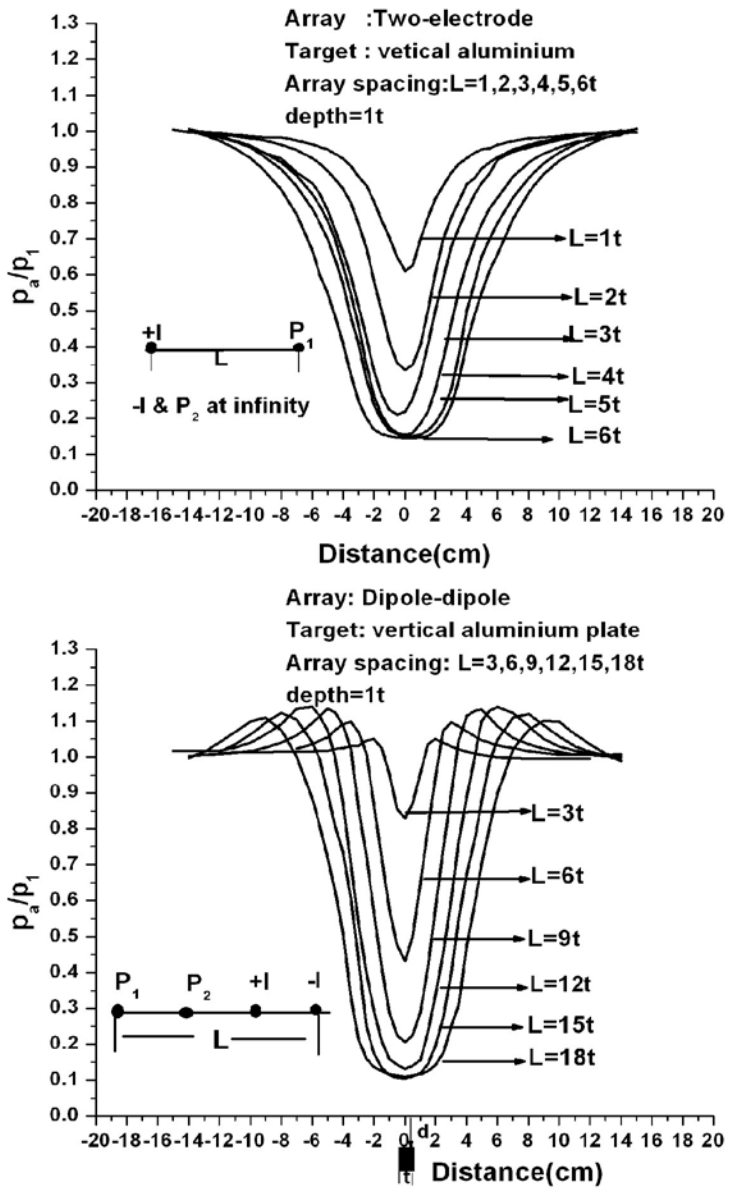

Figure 2. Apparent resistivity profiles with Two-electrode array (above) and Dipole-dipole (below) over metallic target. (Target in vertical position); 'L' varies while'd' is constant.

electrode arrays in order to determine the superiority or otherwise of an array over others. In the present modeling, the thickness of the sheet is taken as unity and all other dimensions, like the distance of the electrode system from centre of the target-sheet, the depth of the target and the dimensions of the target are all expressed in terms of the thickness of the sheet. The host medium is tap water in all the model experiments.

For finding out the relative advantages and disadvantages of the conventional electrode arrays used, we have carried out experimentation in two ways. (i) the target depth is fixed at a particular level and profiles are run with different arrays viz., Two-electrode, Three-electrode, Wenner and Dipole-dipole, changing the array spacings for that particular depth .For this, the conducting target is submerged in the host medium, water, in vertical position ($\theta=90°$) contained in the tank and resistivity response characteristics are recorded for all arrays and their spacings in a systematic and sequential way. These profiles are illustrated in the figures 2 and 3 (ii) the same target is kept in different orientation i.e., in horizontal direction ($\theta=0°$) and its depths are changed for a particular array spacing of the array so that an in-depth understanding of the theme can be had i.e.,

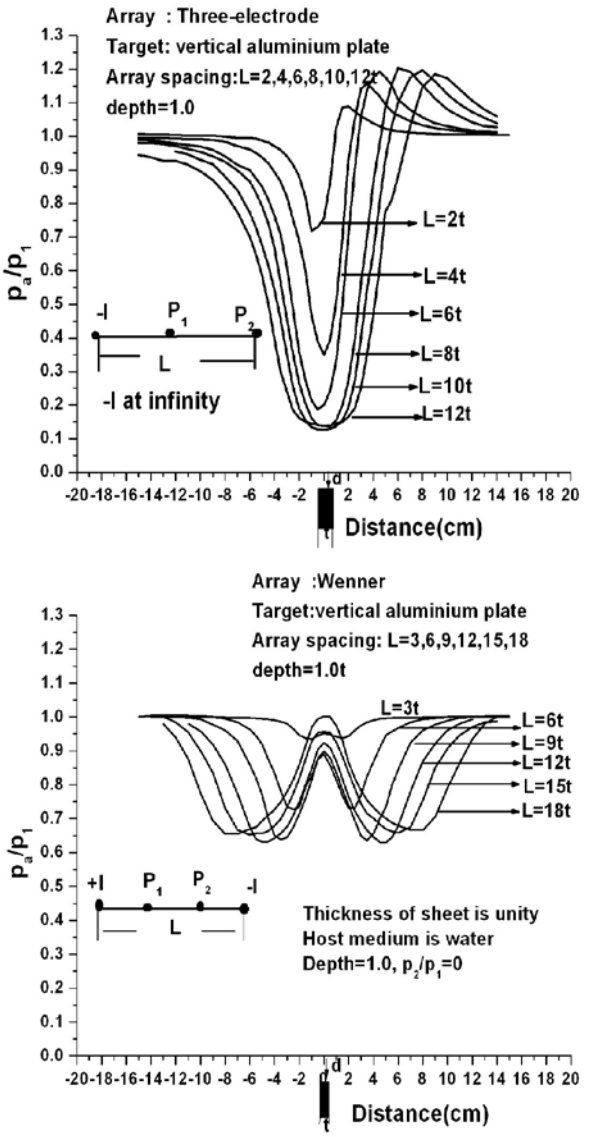

Figure 3. Apparent resistivity profiles with three-electrode array (above) and Wenner(below) over metallic target. (Target in vertical position); 'L' varies while'd' is constant.

variation of the anomaly with depth, with orientation, with array spacing and with type of the array. All the profiles recorded over the horizontal aluminium sheet with different arrays, array spacings, depths are illustrated from figures 4 to 11.

RESULTS AND DISCUSSION

Figure 2 illustrates characteristic resistivity profiles with Two-electrode and Dipole-dipole arrays over vertical aluminium sheet submerged in the host medium, water, in the model tank. Top indicates Two-electrode and bottom Dipole-dipole array. The array spacings and target depths are as mentioned above. The sheet-like target is submerged in the host medium, in the vertical position ($\theta=90°$) at a fixed depth ($d=1.0t$). Measurements have been carried out using resistivity profiling over the target and the resistivity response characteristics have been recorded with all the conventional arrays.

In Two electrode profiling, A resistivity low (trough) observed exactly over the target. This is a symmetric array and the plotting point is taken at the center of the array. With this array, maximum anomaly is observed right over the target. In this, the 'inactive infinite' electrodes are placed diagonally at the corners of the model tank on either side of the array system. The definition of the infinity electrodes is that the distance between the infinity electrodes and the working traverse, where the active electrodes are kept, is at ten times the distance between the active electrodes. Again, while the two- electrode with spacing L= 3, 4 and 5.0 produces apparent resistivity anomaly amplitudes 0.60, .79 and 0.84 respectively the same anomaly amplitudes are produced by the three- electrode profiles (shown in Fig.3) with spacing's L=6, 8 and 10, respectively. This again confirms the theory of depth of investigation developed by Roy and Apparao (1971). According to this, the depth of investigation of three- electrode array is, for the same minimum electrode separation, half that of the two-electrode array.

The Dipole-dipole array (bottom of fig.2) that is used for profiling in the present study is gamma-Wenner where 'n' =1 for operational purposes. In this case, a 'resistivity high (trough)' is observed over the target and two peaks are observed on either side. The anomaly is taken as the difference of amplitude between the 'peak' and 'trough' in each profile.

Profiling curves shown in top panel of fig.3 are obtained using Three electrode array are asymmetric, resembling the asymmetry of the array and is not because of the inclination of the target. The plotting point is taken between current electrode (+I) and the next immediate potential electrode (P^1). It is observed that a trough falls right over the target for all separations. Extreme care must be taken while interpreting the data. The amplitude of the anomaly is taken as the difference between peak value and trough value. In this array, only one infinity electrode (the second current electrode C_2 or sink) is used which is kept at a distance of ten times the array spacing. This array is mostly used to quicken the operational procedure with optimum resolution compared to Wenner and Dipole-Dipole arrays where the four active electrodes are operational from measurement to measurement.

With the profiling curves obtained with minimum spacing ranging from L=3t to 15t are shown in bottom panel of fig.3. The profiles depict bewildering shapes with many peaks and troughs when the target is just a single body. The total number of peaks and troughs in a profile is equal to the number of active electrodes of the array plus one. Further, the curves indicate almost a W-shape for all the sizes of the array ,which are smooth in nature. A maximum peak is observed right over the target and the same observation is found in all the curves over the conducting target. The anomaly is taken as the amplitude difference between the peak and trough of a particular array separation. While the apparent resistivity profiles show W- shaped pattern, the explanation for the central apparent resistivity peak value of 1.0 right over the target is like this: For homogeneous ground with Wenner (or Schlumberger) array, the vertical half- plane passing through centre of the array is an equi-potential surface of zero value. If this plane is occupied by a thin infinitely conducting sheet either wholly or in part, the potential distribution will not change. Hence, the apparent resistivity that is measured in presence of the conducting sheet will be the same as in the homogeneous ground when the sheet is removed. While doing the interpretation of field profiles , this observation must be kept in mind because the field curves are never so smooth as those obtained in the lab for a similar situation.

We have also repeated the similar experimentation over horizontal aluminium sheet. The resistivity response of the electrode arrays is different compared

to vertical conducting sheet. That is; in the case of horizontal sheet ($\theta = 0°$), the array size (L) is fixed and the target depth (d) is kept on changing whereas the target depth is fixed and array size is kept on changing for vertical sheet ($\theta = 90°$). All these profiles are illustrated in the figures from 4 to 11.

In the case of two-electrode array over the horizontal aluminium sheet (figures 4 and 5), a resistivity low is observed exactly over the target for all profiles, which is similar to that over vertical sheet. As depth of the target increases, the amplitude of the anomaly decreases for all spacings. Also, as array size (L) increases, a smooth hump is observed for shallow depths at larger array spacings; and with increasing target depth (d) the smooth and slight hump totally disappears resulting in just smooth profiles only. The fixing of the infinity electrodes in this case is similar as in the earlier case i.e., at the diagonal corners of the model tank only.

In the case of Three-electrode array (figures 6 and 7), all the profiles are asymmetric only pattern as the array itself is asymmetric in nature. A slight hump is also observed for larger array size at shallow depth. A peak is observed on the right of the target in all the profiles. However, if another reverse profile is run over the same target with reverse positioning of electrodes, then the right hand side peak is shifted to left hand side and this may result in the easy interpretation of the data for investigating the location of the targets. A similar results are observed in the case of vertical sheet also.

The profiling curves using Dipole-Dipole array over the horizontal conducting sheet are shown in Figures 8 and 9. The amplitude of the anomaly is decreasing with increasing depth, which is similar to earlier results. All the profiles are flanked by two peaks on either side of the trough. Concurrently, the reflections of the target are indicated in the

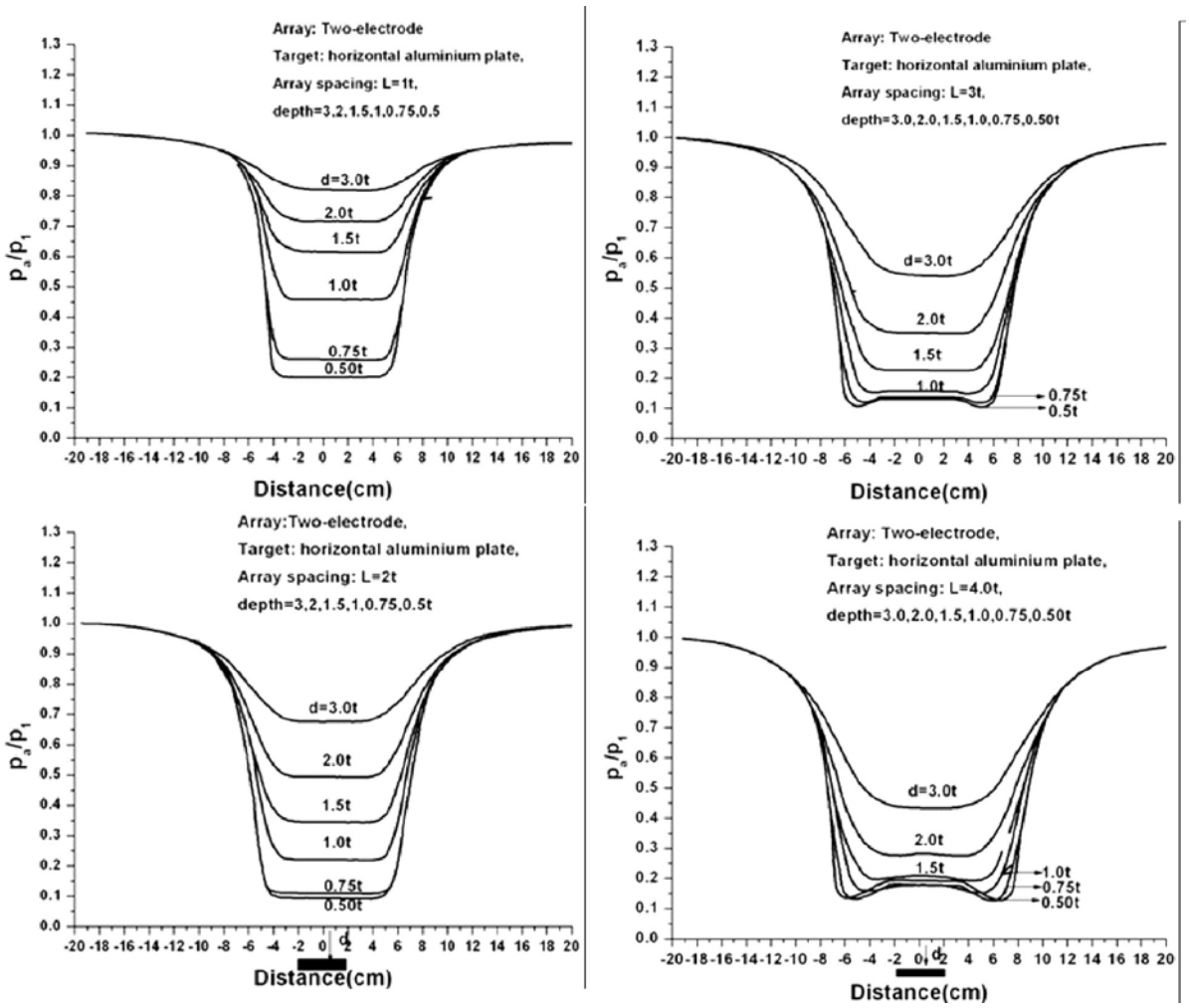

Figure 4. Two-electrode array over horizontal plate ($\theta = 0°$) keeping sapcing (L)

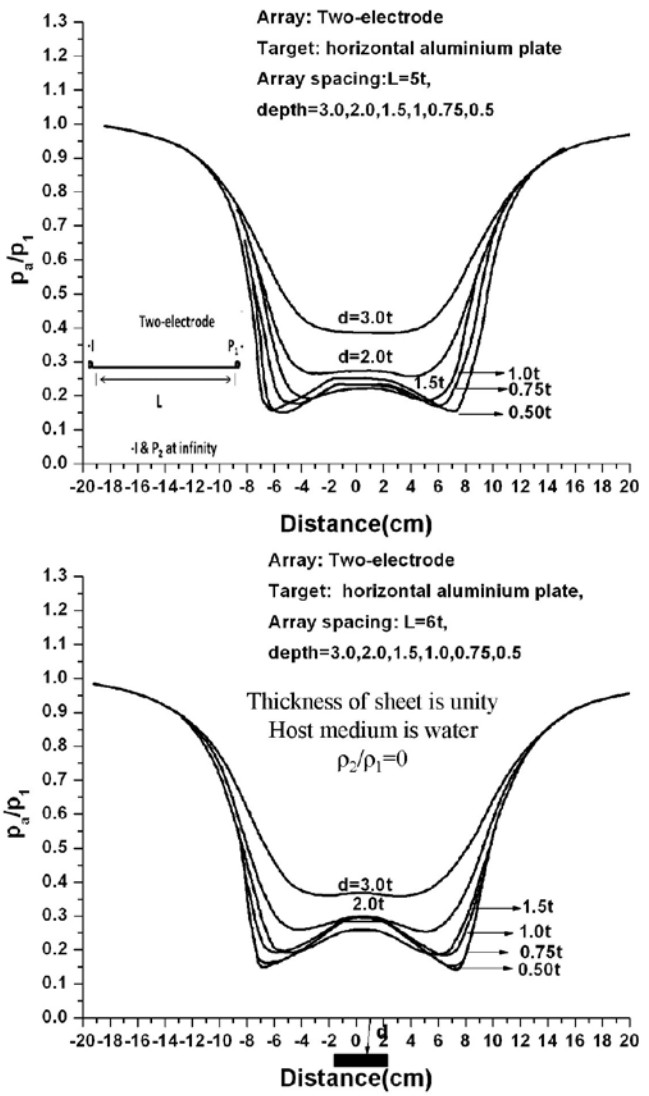

Figure 5. Two-electrode configuration over horizontal plate ($\theta = 0°$) keeping spacing (L) constant and depth (d) varying..

trough of each profile. Symmetry of Dipole-Dipole array provides an ease in the identification of target location. Further, with increasing depth, the major trough is also surrounded by two more mini troughs on either side, which smoothly subsides as the array size increases. Two-electrode troughs (resistivity low) are similar to Dipole-dipole troughs, but the difference is that there are no peaks on either side.

With Wenner array profiles (figures 10 and 11) are totally a different. A simple low, indicating presence of the target is seen. One can notice that a W-shape is observed over a vertical conducting sheet, where as it is a flat low over the horizontal sheet indicating the target presence. These flat lows are also having mini-lows on either side at lower depth levels.

CONCLUSIONS

Physical model experimentation has been carried out over an infinitely conducting target (aluminium sheet) of dimensions 100x10x1 cm. The resistivity profiles are obtained over the target both in vertical and horizontal positions at various depths using Wenner, Two-electrode, Three-electrode and dipole dipole arrays and the relative merits and demerits are analyzed in the present study to find out the relative merits and demerits of the arrays and to study the efficacy of one electrode configuration over

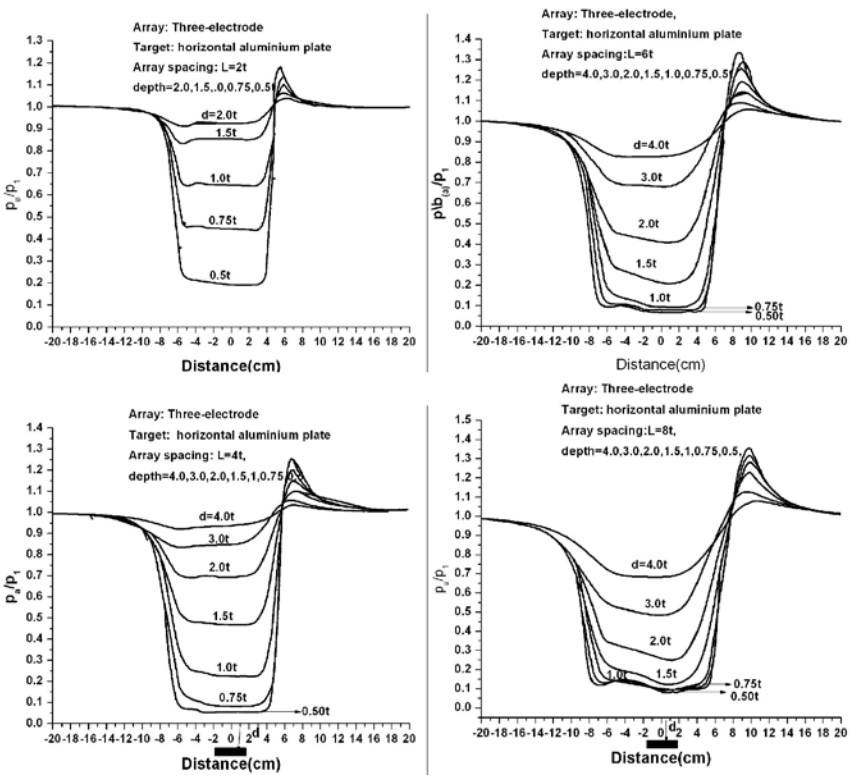

Figure 6. Three-electrode configuration over horizontal plate (θ = 0°) keeping spacing (L) constant and depth (d) varying.

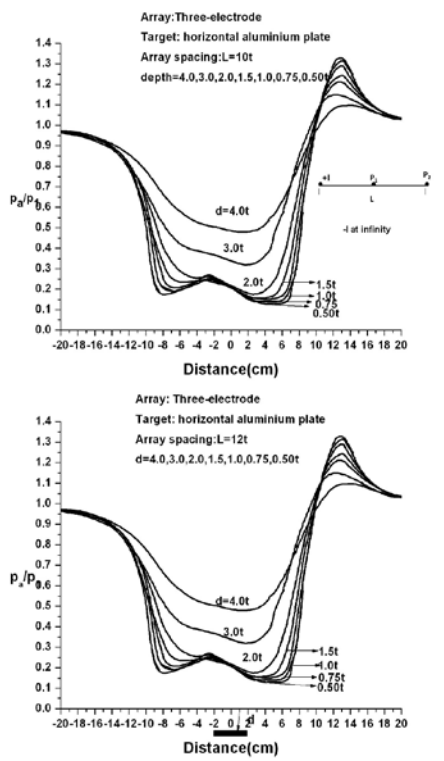

Figure 7. Three-electrode configuration over horizontal plate (θ = 0°) keeping spacing (L) constant and depth (d) varying.

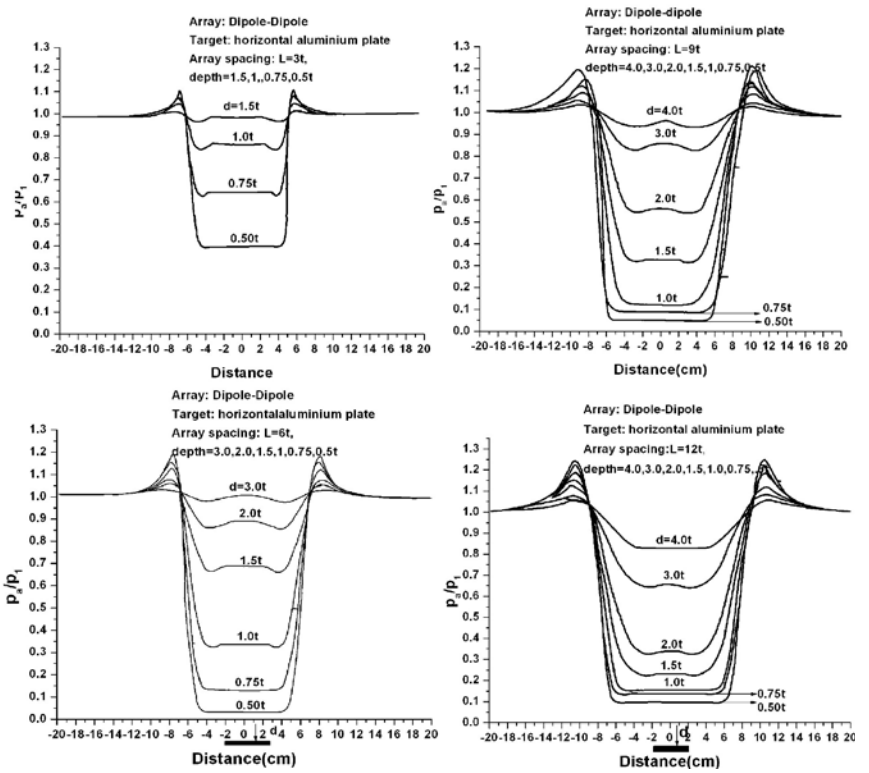

Figure 8. Dipole-dipole configuration over horizontal plate (θ = 0°) keeping spacing (L) constant and depth (d) Varying.

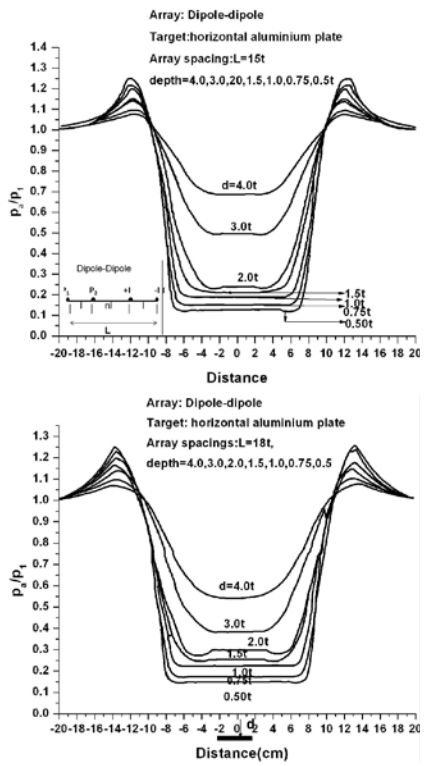

Figure 9. Dipole-dipole configuration over horizontal plate (θ = 0°) keeping spacing (L) constant and depth (d) varying.

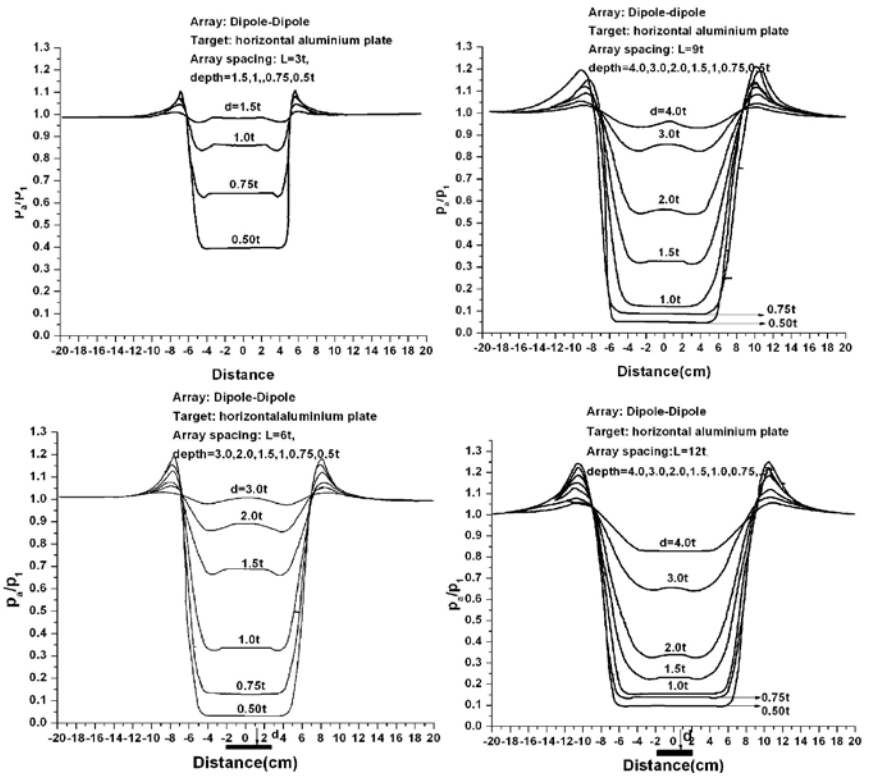

Figure 10. Wenner configuration over horizontal plate (θ = 0°) keeping spacing (L) constant and depth (d) Varying.

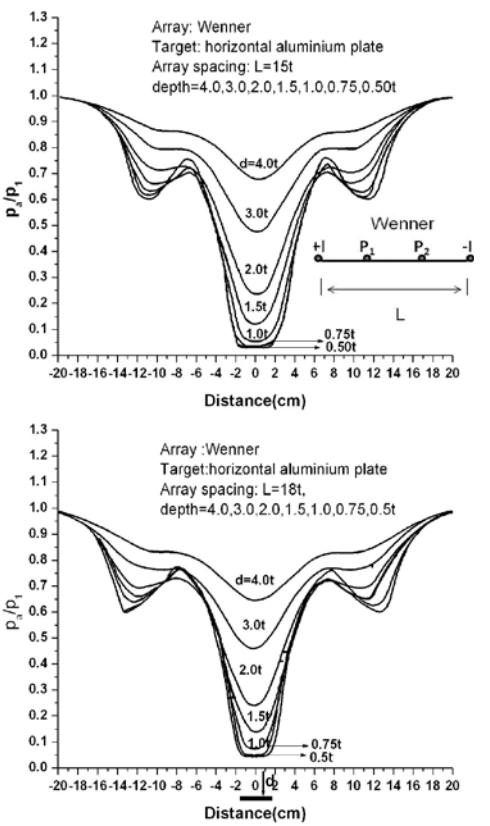

Figure 11. Wenner configuration over horizontal plate (θ = 0°) keeping spacing (L) constant and depth (d) Varying.

the other. Over the vertical conducting sheet, the apparent Wenner resistivity profiles show a W-shaped pattern, where as a low is observed over horizontal sheet. The amplitude of the anomaly is maximum with Two-electrode and it is minimum with Wenner. Asymmetric shape of the curves is observed with Three-electrode array. The Dipole-Dipole curves are symmetric in nature and anomaly is significant.

The other result that emerged out of the comparison of the different electrode arrays is that the two-electrode array gives the simplest and largest anomalies with the shortest of spacings over conducting metallic target. This array gives the best response with regard to amplitude and shape of the anomaly. This means that for a given spacing, the depth of investigation is much larger with the Two-electrode array than with the other arrays. Secondly, the Two-electrode array requires less transmitting source power and less number of helpers and hence moves faster for field operation; thereby resulting in minimum cost of operation. For deeper investigation, the electrode spacing has to be large. In such a case, the distant electrodes (infinity electrodes) in the Two-electrode array have to be planted at far- off distance. This limits the use of the array for deeper investigations. For such a situation, the Dipole -Dipole array is the next alternative as its response is symmetrical, better in shape and amplitude over a metallic sheet.

An overall study on efficacy of the electrode arrays over both the target orientations indicated that the profiles are broadened over horizontal conducting sheet compared to those over a vertical sheet. The reason is that in the case of horizontal sheet, the area of exposure to the measuring system is very large in comparison with the exposed area of vertical sheet. To argue in a simpler way, the target dimensions are: length=100cm, width=10cm and thickness=1 cm. In the case of vertical sheet, only thickness area is exposed and where as for horizontal sheet, the width area is exposed .This results in ten times more exposed area for horizontal sheet compared to vertical sheet, and hence the profiles are to be widened.

If the array spacing/size is not considered as a yard stick for comparison and the availability of the source power is not a problem in the field, and as such the Dipole-Dipole array does seem to be superior to the other arrays. The Three-electrode array seems to be a compromise, in which case only one current electrode (sink or -I) needs to be kept at infinity as it does not require as much source power as the Dipole-Dipole array needs. But, at the same time, the anomalies with the Three-electrode array are asymmetrical and, hence, may pose a problem in the interpretation of the field data. It may, however, be noted that, the dipole array can be used to obtain larger depth of investigation without any difficulty in field operation, there is limitation to increase the spacing of two-electrode array, because the infinity electrodes have to be kept correspondingly farther, at least more than ten times the spacing. But, for larger spacing, dipole array however, carries the disadvantage (limitation) that it requires large source power and/or sensitive voltage measuring receiver.

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