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Electrical Resistivity Behaviour of Layered Soil System

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Introduction

Geotechnical engineers have well realized the importance of Geophysical methods for subsurface explorations. Electrical resistivity is one such non-destructive method, which is now being increasingly used as a complementary to direct and semi-direct methods of exploration due to manifold merits it possesses over other indirect methods of exploration. The electrical resistivity soundings at a field location provide the values of apparent resistivities at different depths of sub-surface strata. The apparent resistivity up to any particular depth is a function of true resistivities and thicknesses of various strata through which the current passes. In order to obtain subsurface profiles (bore hole logs), it is imperative to interpret field electrical resistivity soundings data to derive true resistivities and thicknesses of strata.

There are a number of interpretation techniques available for evaluating true resistivity and thickness of each of the stratum from resistivity sounding curves as proposed by many investigators. These techniques can be grouped as graphical, analytical, numerical, computer (software) based, etc. and several amongst each group. Each technique is based on a separate approach of interpretation and methodology. The literature review points out that very little work has been done to understand the limitations, suitability, accuracy and reliability of these techniques in relation to different sub-surface conditions including layer sequence and their resistivity ratios. Kate and Khichchu Mal (1983) conducted vertical electrical resistivity soundings in the field and compared the results of resistivity and thickness of subsurface strata interpreted by different graphical techniques with the ground truth obtained from bore holes drilled at these locations. They noticed certain drawbacks associated with these techniques and reported that, the interpreted results were not comparable with the ground truth.

In view of the practical difficulties normally faced in the field to conduct studies under controlled conditions, present laboratory investigation has been planned to understand electrical resistivity behaviour of layered soil system under controlled conditions. An attempt has been made to interpret the laboratory electrical resistivity sounding results by using different interpretation techniques commonly practiced by investigators. The interpreted values have

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been compared with the actual values of resistivity and layer thicknesses to assess the limitations and reliability of these techniques.

Literature Review

True resistivity and apparent resistivity

The true electrical resistivity (ρ) is fundamental property of the material, which is independent of volume and remains constant for the isotropic and homogeneous material. The values of ρ for geo-materials can be determined in the laboratory using two-electrode (Kate, 1995) or four-electrode method. For an-isotropic, non-homogeneous and stratified/layered subsurface materials the resistivity does not remain constant throughout the depth of such deposit. The effective resistivity value measured for layered deposit is referred as mean or apparent resistivity (ρ_a). The apparent resistivity which is a function of true resistivities and thicknesses of various subsurface strata through which current flows can be expressed as,

$$\rho_a = f\left[\{ \rho_1, h_1 \}, \{ \rho_2, h_2 \} \ldots\ldots\ldots \{ \rho_n, \overline{h}_n \} \right] \tag{1}$$

Where, ρ_a is apparent resistivity of horizontally stratified (layered earth) system up to a depth (which includes part thickness $\overline{h}_n$ of n[th] layer) of current penetration (array spacing/electrode separation), *a* below the ground surface. The notations $\rho_1, \rho_2 \ldots\ldots \rho_n$ are true resistivities of layers 1, 2, …….. n respectively and $h_1, h_2 \ldots\ldots h_n$ are their thicknesses. The value of ρ_a will be equal to ρ_1 for homogeneous surface stratum as long as $a \leq h_1$. The magnitude of $\overline{h}_n$ is obtained by Eq. (2) given below.

$$\overline{h}_n = a - \left(h_1 + h_2 + \ldots\ldots.. h_{n-1} \right) \tag{2}$$

The mathematical expression for apparent resistivity measured over a horizontally stratified system is usually derived in the form of a Hankel transform integral (Keller, 1974). For example, for the Schlumberger circuit array arrangement, apparent resistivity is given by:

$$\rho_a = \rho_1 \int_0^{\infty} K\left(m, \rho_i, h_i \right) m J_1 \left(m a \right) dm, \tag{3}$$

Where ρ_i and h_i are the resistivity and thickness of the i[th] layer, *m* is a dummy variable without physical meaning, *K* ( ) is a “kernel” function containing all the available information about resistivity variation with depth and J_1 is Bessel’s function of the first kind of order one.

Resistivity Soundings

Resistivity soundings at a field location provide the values of apparent resistivities at different depths of subsurface strata beneath. The resistivity survey in the field is carried out by driving 4 electrodes spaced at a known distance along a straight line. For engineering applications the commonly practiced electrode configurations are Wenner circuit array and Schlumberger circuit array. The schematic arrangement of layout of electrodes is illustrated in Figure 1 for Wenner circuit array. A current of electricity is passed between the two outer electrodes C_1 and C_2 and the difference of potential between the two inner electrodes P_1 and P_2 is measured. It is assumed that an equipotential hemisphere is set up around each of the two outside current electrodes. Every point on the surface of a hemisphere is at the same potential due to the current (I) flowing between electrodes C_1 and C_2. The potential drop (E) between the two hemispheres is measured by a separate potential measuring circuit through potential electrodes P_1 and P_2 placed on the ground where the equipotential hemispheres intersect the ground surface.

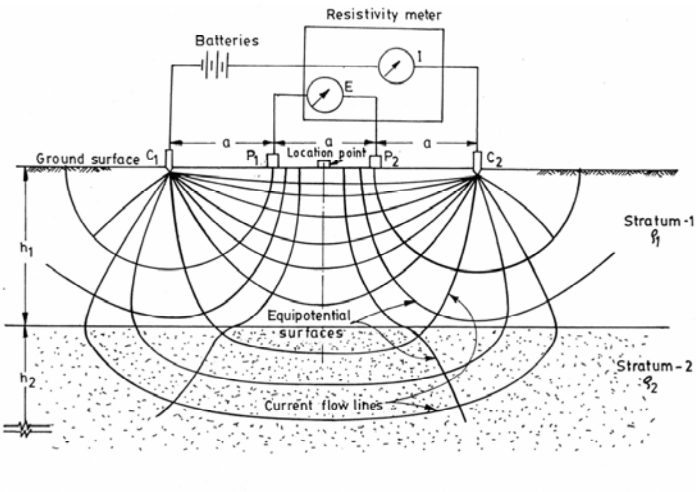

Fig. 1 Schematic Arrangement of Field Resistivity Sounding by Wenner Circuit Array

Figure 1 also illustrates as to how the current flow lines get deflected while entering into another layer of different resistivity. The pattern of deflection of current flow lines and consequently equipotential lines depends on the sequence and relative resistivity values of layers i.e. low resistivity layer underlying high resistivity layer and vice versa. The depth of current penetration into the ground depends on the geometrical layout and spacings of the electrodes. By increasing the electrode spacing, the depth of current penetration into ground can be increased, thereby the resistivities of subsurface strata at different depths can be investigated. The apparent resistivity at a given depth is calculated from Eq. (4) for Wenner's and by Eq. (5) for Schlumberger's circuit array.

$$\rho_a = 2\,\pi\,a\,\frac{E}{I} = 2\,\pi\,a\,R \tag{4}$$

In which, a is electrode spacings (Figure1) and R is resistance. The depth to which the current penetrates into the ground is also equal to a in Wenner circuit array.

$$\rho_a = \frac{\pi}{2} \times \frac{E}{I}\left(\frac{a^2 - b^2}{b}\right) = \frac{\pi}{2} . R \left(\frac{a^2 - b^2}{b}\right) \tag{5}$$

Wherein,

2a = Spacing between current electrodes C_1 and C_2 , and

2b = Spacing between potential electrodes P_1 and P_2.

The depth of current penetration in Schlumberger circuit array would be half the spacing between current electrodes i.e. equal to *a*.

Interpretation of field data

The interpretation of vertical electrical soundings data basically involves converting/transforming apparent electrical resistivity (ρ_a) values recorded at different current penetration depths (electrode separations, *a*) into true resistivity (ρ) and thicknesses (*h*) of various subsurface strata through which the electric current passes. Thus, it is the process of deriving the values of $\rho_1, \rho_2, ...\rho_n$ and h_1, h_2 ……. h_{n-1} from the recorded values of $\rho_{a1}, \rho_{a2} .....\rho_{an}$ at electrode separations of a_1, a_2 ……. a_n as per Equations (1) and (3). It is worth mentioning here that the full thickness of n^{th} layer h_n can be estimated only when the current penetrates down into $(n+1)^{th}$ layer.

In order to interpret resistivity soundings data, the commonly practiced techniques other than computer software and standard curve matching (Compagnie General de Geophysique, 1963) are Inverse slope (Sankar Narayan et al., 1967), Barnes layer (Barnes, 1954), Direct slope (Baig, 1980), Moore's cumulative plot (Moore, 1961) and Hummel's principle (Hummel, 1931). Moore's cumulative plot is completely graphical method, which reliably provides the thicknesses of layers but has limitations to estimate true resistivity values. On the other hand, Hummel's principle is an analytical approach, which furnishes true resistivity of layers but has limitation to provide layers thicknesses. However, the combination of these methods referred as 'Moore with Hummel extension' can reliably interprete magnitudes of both the true resistivity as well as thickness of layers. All these techniques, in general, fall in a group of graphical methods.

Laboratory and Field Investigation

Laboratory investigation conducted by Kate (1978) on layered combination of four dry soils namely clay, silty loam, fine sand and gravel with each soil layer compacted to a thickness of 6 cm. He reported sudden change in apparent resistivity at the interface of layers as the current penetrates down into various layers. The values of apparent resistivity at different depths indicated combined/mixed effect of true resistivities of various layers. It is interesting to note that Kate (1978) observed an increase in resistivity with increase in compaction density for dry soils, whereas Chauhan and Kate (1983) reported decrease in electrical resistivity with increasing compaction density for saturated soils. This clearly indicated that the effect of moisture changes on resistivity of soil as compared to that of density is considerably high to an extent to cause reversal of variations trend.

Laboratory model studies were conducted by Kate and Shamsher (1988) to understand resistivity behaviour with depth in single layer soil compacted dry under controlled conditions of density. They compared the results of resistivity soundings as interpreted by different interpretation techniques and reported that each technique provides values which are practically not in agreement with each other. They noticed an increase in resistivity with depth which was attributed to increase in density of lower layers as a result of transmission of progressive compaction energy while compacting the upper layers.

Vertical electrical resistivity soundings were carried out in the field by Kate and Khichchu Mal (1983) and at the same locations bore holes were drilled. They compared the results of interpreted values of resistivity (ρ_i) and thicknesses (t_i) of different sub-surface strata obtained by various interpretation techniques from resistivity sounding curves with the true values of ρ and t obtained from actual bore hole data. The comparative study reported by them highlighted suitability and limitations of these techniques in the context of accuracy of data interpretation, depth to be explored, number and sequence of strata, etc.

Experimental Programme

The present laboratory study has been conducted on completely dry soils having high resistivities. Two soils chosen for this investigation exhibit considerable difference in their true resistivity values in dry condition. The details of instruments and accessories used, soils studied, experimental procedure adopted and the parameters varied are given in the subsequent sections.

Instruments

The instruments namely Power Unit, Micro Ammeter and Digital Voltmeter used were highly sensitive so as to record the corresponding values very precisely. The Power Unit with capacity to stabilize the voltage range from 0-40 Volt, was used for constant Direct Current supply through laboratory mains. The digital micro ammeter with range to read from 0.3 to 300 micro Amperes has been used to measure the current.

The digital voltmeter having range from 100 milli-Volts to 400 Volts was used to measure the potential difference developed between the potential electrodes. The electrodes were made of copper rods of 6 mm diameter and 22.5 cm length. Figure 2 shows the circuit diagram and schematic arrangement of experimental set-up used for measuring soil resistivity.

Accessories

The accessories required were specially fabricated. These are a well stiffened wooden tank of internal dimensions 244 cm $\times$ 30 cm $\times$ 83 cm , a wooden leveller with handle and a compaction device made up of mild steel comprising of base plate with collar in its centre and handles to lift the device during soil compaction.

A wooden scale of width 10 cm and length equal to that of wooden tank was fabricated. The holes of 6 mm diameter at 2.5 cm intervals were drilled all along the length of the scale. These holes facilitate driving/pushing of electrodes into the soil at desired spacing accurately.

Soils

The investigation has been conducted using two soils namely Delhi silt and Yamuna sand. Delhi silt has percentages of sand, silt and clay sizes of 29%, 57% and 14% respectively. It has liquid limit, plasticity index and shrinkage limit of 33%, 10% and 21% respectively and is classified as silt, sandy with low plasticity *(ML)*. Yamuna sand has 100% sand size particles and it's maximum and minimum unit weights are 17.5 and 13.5 kN/m^3 respectively. The angle of shearing resistance of this sand is around 42°.

Experimental Procedure

The dry soils were compacted in the wooden tank at desired dry unit weights (γ_d) in lifts of 5 cm, until the desired thickness of layer was reached. The compaction procedure adopted here is similar to that adopted by Kate and Shamsher (1988). The soil surface was levelled and a wooden scale was placed in the centre of the tank along it's length. The electrodes were pushed through the scale holes into the soil for about 5 cm deep ensuring good contact between electrodes and soil. The electrodes were arranged as per Wenner circuit array with electrical connections between electrodes and the instruments made as shown in Figure 2. The power unit was switched on and the observations for current and potential difference were recorded. The electrode spacing was then increased and the procedure was repeated for different electrode spacings. The electrode spacings (*a*) were increased by 5 cm until the desired depth of current penetration was reached. The Equation (4) has been used to calculate the apparent resistivity at different depths.

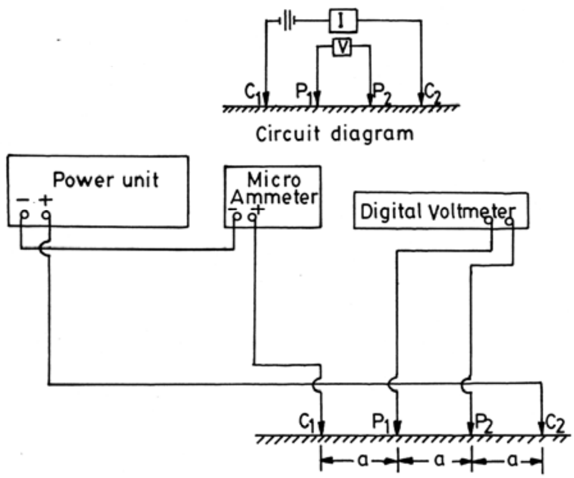

Fig. 2 Circuit Diagram and Arrangement for Measurement of Soil Resistivity

Parameters Studied

All the experiments to understand electrical resistivity behaviour of single layer and two layer soil systems have been conducted adopting Wenner circuit array by varying the following parameters.

Single layer soil system: Each soil (Delhi silt or Yamuna sand) has been compacted at γ_d of 15 kN/m^3 to a maximum layer thickness of 80 cm. During compaction, the observations of *E* and *I* have been recorded for the progressing sub-layers having cumulative thicknesses of 20 cm, 40 cm, 60 cm and 80 cm.

Two layer soil system: This comprised first case of Delhi silt as upper layer and Yamuna sand as bottom layer and vice-versa in second case. The thickness of bottom and top layers has been kept at 40 cm each, thus the maximum total thickness of two layered soil system becomes 80 cm. In each case, the compaction γ_d for the bottom layer has been maintained constant at 15 kN/m^3 whereas, the γ_d of the top layer has been varied. The compaction γ_d for Delhi silt as top layer varied are 13.5, 14.0, 14.5 and 15 kN/m^3. For Yamuna sand as a top layer these γ_d varied are 15, 16 and 17 kN/m^3. The electrical resistivity sounding observations for the layered soil system have been taken at the progressing fill thicknesses of 20 cm, 40 cm, 60 cm and 80 cm.

Specific Studies: In order to understand the influence of progressive compaction energy being transmitted to already compacted layers beneath while compacting the upper layers on the unit weight of soil, these studies have been carried out. The observations of unit weights with depth have been taken using a specially fabricated perspex sampling tube (with detachable base disc) of 5 cm dia. and 7.5 cm height. These observations have been taken at the end of the experiments conducted on Delhi silt as well as Yamuna sand compacted as single layer at initial compaction unit weight of 15 kN/m^3 up to a thickness of 80 cm. The electrical resistivity of soil samples thus obtained have been measured by adopting two electrode method similar to that by Chauhan and Kate (1983). The values of unit weights (γ_d) at different depths and true electrical resistivity (ρ) thus obtained are presented in Table 1.

Table 1: The Unit Weights and True Electrical Resistivity at Different Depths

Depth (cm)	Delhi silt		Yamuna sand	
	γ_d (kN/m^3)	ρ (Ohm.cm)	γ_d (kN/m^3)	ρ (Ohm.cm)
0	15.000	1.8×10^5	15.00	1.4×10^7
20	15.215	1.02×10^6	15.50	8.3×10^7
40	15.535	4.1×10^6	16.10	2.8×10^8
60	15.640	9.6×10^6	16.15	5.9×10^8
80	15.760	2.1×10^7	16.20	8.2×10^8

Presentation and Discussion

Single layer soil system

The compacted soil layers starting from the bottom of wooden tank follows a rising sequence as sub-layer I, II, III and IV each 20 cm thick as illustrated in Figure 3 and Figure 4. In order to simulate field condition (wherein ground level is datum) the surface of soil layer of total thickness of 80 cm has been considered as a datum (i.e. depth of current penetration or electrode spacing, *a* = 0, and *a* values measured below this surface. Accordingly, the surfaces of sub-layers I, II, III and IV correspond to values of *a* equal to 60, 40, 20 and 0 cm respectively. The variation between electrode spacings and resistivity ρ illustrated in Figure 3 and Figure 4 corresponds to Delhi Silt and Yamuna sand respectively for each soil compacted at γ_d = 15 kN/m^3. The variational curves in these Figures correspond to the observations of sub-layers I, II, III and IV taken after their compacted cumulative thicknesses reached to 20, 40, 60 and 80 cm respectively. The following observations can be noticed from these Figures.

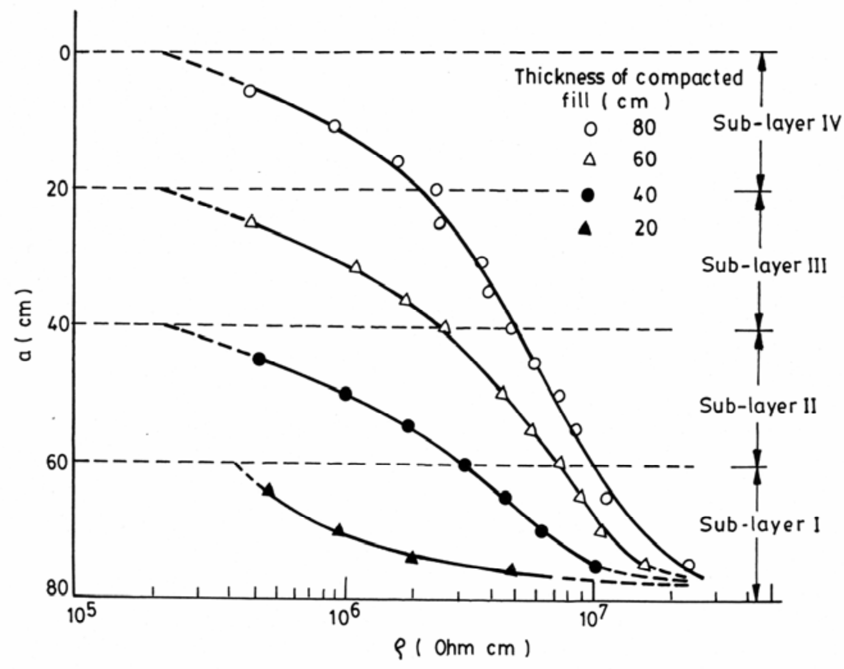

Fig. 3 Resistivity Variation with Electrode Spacings for Single Layer Delhi Silt

(i) At the same depth of current penetration (*a*) below the surface of each sub-layer, the ρ values are more or less the same e.g. for Delhi Silt, ρ values at 10 cm current penetration depth below the sub-layers I, II, III and IV are 9.1 $\times$ 10^5, 9.2 $\times$ 10^5, 9.25 $\times$ 10^5 and 8.95 $\times$ 10^5 Ohm.cm respectively. This corroborates well with the fact that for surface layer of homogenous and isotropic soil, the resistivity values should remain constant throughout its depth as in this case the apparent and true resistivities are virtually the same.

(ii) All the curves for each and every sub-layer shows increase in ρ with *a*. The variation noticed in this case can mostly be attributed to increase in unit weights of the lower layers as a result of progressive compaction energy being transmitted into them while compacting the upper layers (Kate and Shamsher, 1988). The observation in case (i) corresponds to uniform unit weight of all sub-layers at the same depth of current penetration.

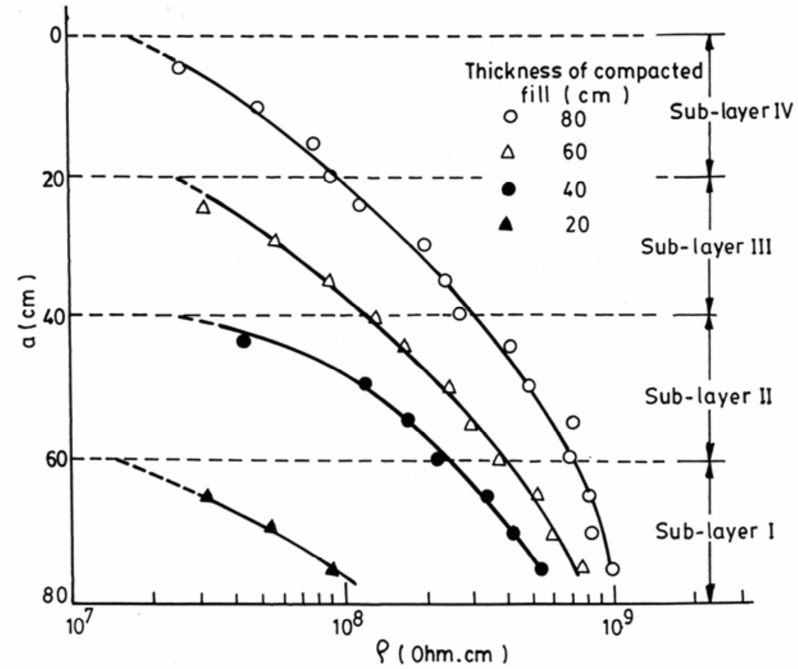

Fig. 4 Resistivity Versus Electrode Spacing for Single Layer Yamuna Sand

Two layer soil system

Low resistivity layer over high resistivity layer

The variations between the electrode spacings and corresponding resistivity obtained for Delhi silt over Yamuna sand system are illustrated in Figure 5, Figure 6 and Figure 7 for Delhi silt compacted at γ_d of 13.5, 14 and 14.5 kN/m^3 respectively. The depth of current penetration has been corrected to identify the same existing layer for which resistivity observation corresponds. These Figures show that the apparent resistivity increases through both the layers as the current penetrates deeper and deeper.

For brief and simple explanation of the results, electrode spacings versus apparent resistivity curves for two layered soil system have been designated by ABC, A'B'C' and D'DE. The part DE of the curve D'DE indicates the variation of electrode spacings with apparent resistivity for Yamuna sand alone at compacted thickness of 40 cm with part D'D extrapolated to meet the interface. The curve A'B'C' indicates the variation between electrode spacings and apparent resistivity for the two layer system, where in observations have been taken for the compacted thickness of 60 cm comprising of Delhi silt of 20 cm above interface and Yamuna sand layer of 40 cm thickness with B' as the point on this curve at the interface. Similarly, curve ABC is for the final thickness of 80 cm of two layered system and B is the interface point in this case. These designations have been adopted to all such curves for other thicknesses of compacted layers.

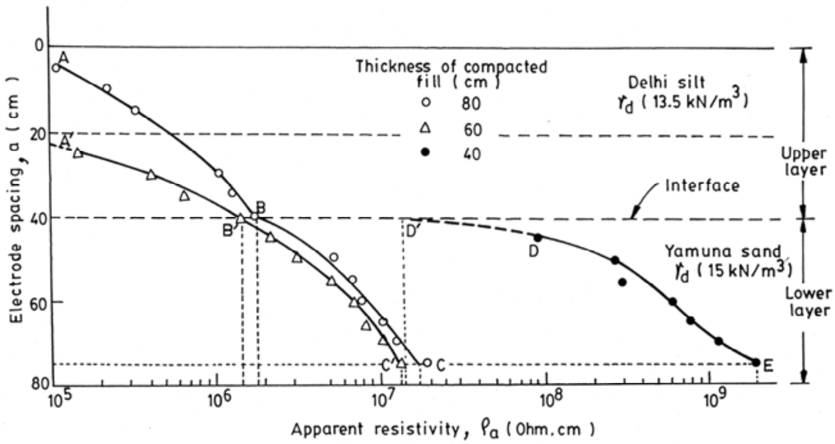

Fig. 5 Variation of ρ_a with a for Delhi Silt (γ_d = 13.5 kN/m^3) Overlying Yamuna Sand

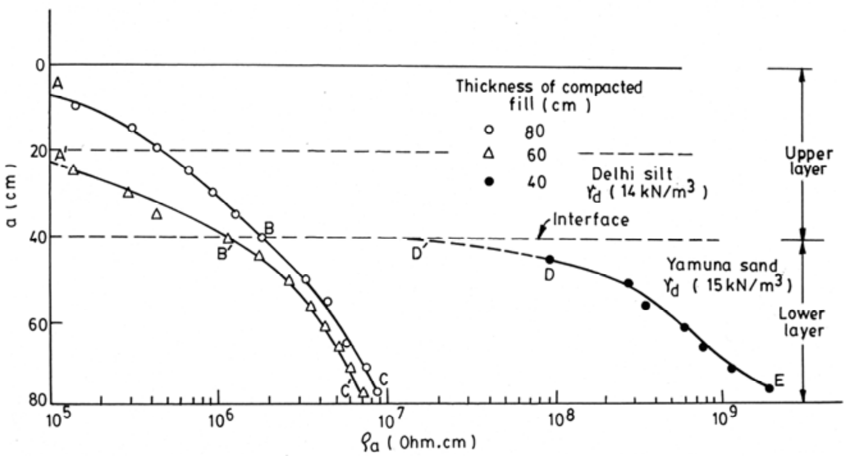

Fig. 6 Variation of ρ_a with a for Delhi silt (γ_d=14kN/m^3) Overlying Yamuna Sand

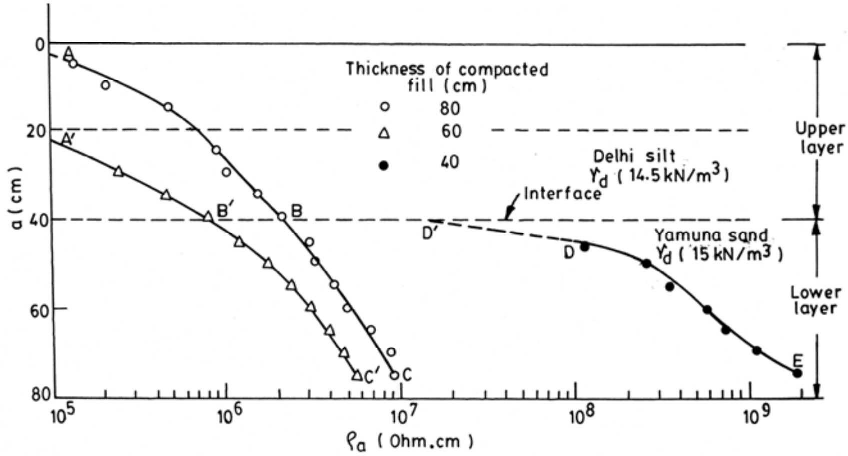

Fig. 7 Variation of ρ_a with a for Delhi silt (γ_d=14.5 kN/m^3) Overlying Yamuna Sand

Referring to the Figures 5, 6 and 7, all the three curves i.e. ABC, A'B'C' and D'DE show increase in apparent resistivity with depth of current penetration. The ranges of resistivity values exhibited by curve D'DE are considerably higher than those indicated by AB or A'B'. This is due to the fact that, the curve D'DE is exclusively for one layer Yamuna sand, whereas the curves AB and A'B' corresponds to Delhi silt which has low resistivity than Yamuna sand. As soon as the current penetrates below interface (points B and B'), the resistivity values tend to exhibit the combined effect of the resistivities of both the soils along with depth of current penetration (partial thickness $\overline{h_n}$) in bottom layer. Thus curves BC and B'C' indicate the combined effect of resistivity of each of these soil layers on the resistivity values measured below interface. The difference in ρ_a values at the bottom layer given by CE is considerably more than that at the interface given by BD' e.g. in Figure 5 the value of BD' is only 1.195×10^7 Ohm.cm, whereas the value of CE is 1.68×10^9 Ohm.cm. It is interesting to note that the difference between ρ_a values at points D' and E is significantly large than that between B and C e.g. in the same figure the difference in ρ_a between D' and E is 1.70×10^9 Ohm.cm, whereas between B and C is only 1.6×10^7 Ohm.cm. It can be observed that the ρ_a values are more pronounced by high resistivity layer as the depth of current penetration below interface increases. The marginal difference between ρ_a values of curve ABC and A'B'C' reflects on the slight increase in unit weight of lower sub-layers while compacting upper sub-layers as illustrated in Table 1.

The variation between apparent resistivity and electrode spacing is illustrated in Figure 8 for various initial compaction dry unit weights of Delhi silt as upper layer. As the ρ_a values in this case falls within narrow range, linear scale has been adopted for ρ_a axis. The variation curves clearly indicate increase in resistivity with increase in dry unit weight at all the levels of current penetration depths. These variations observed here are in agreement with those noticed by Kate (1978) & Kate and Shamsher (1988).

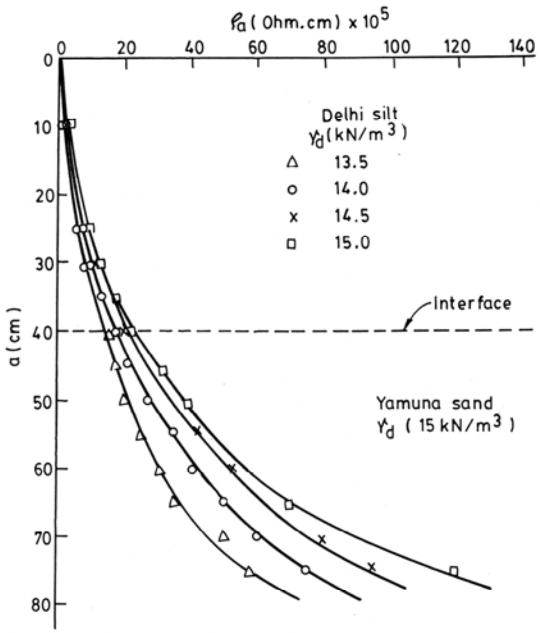

Fig. 8 Apparent Resistivity as a Function of Electrode spacing for Delhi Silt

High resistivity layer over low resistivity layer

The results of ρ_a at different *a* obtained for Yamuna sand overlying Delhi silt are illustrated in Figure 9 and Figure 10 for the compaction γ_d of Yamuna sand of 16 and 17 kN/m^3 respectively. The curves in these figures show that the apparent resistivity increases with depth initially through upper layer and below interface it starts decreasing as the current penetrates deeper into lower layer. Referring back to the designations of curves adopted in previous case, the curve D' DE corresponds to Delhi silt alone as a single layer in this case. The curves ABC and A'B'C' have been extrapolated upto thicknesses of 80 cm (*a* = 0 cm) and 60 cm *(a* = 20 cm) to touch at surface points A_1 and A_2 respectively. It is seen from Figure 9 and Figure 10 that, the ranges of resistivity values exhibited by curve D'DE are much lower than those indicated by B'C' and BC. This is because the curve D'DE is exclusively for single layer Delhi silt, whereas the curves B'C' and BC show the combined effect of resistivity of both the soils (Yamuna sand having higher resistivity than Delhi silt). Thus D'B' and D'B indicate the increase in resistivity at the interface due to combined effect. It is interesting to note that the curves B'C' and BC in Figures 9 and 10 exhibit convexity inwards in contrast to those in Figures 5, 6 and 7, which show convexity outwards. This reflects on to the changes in deflection patterns of current flow lines and equipotential lines below interface as a result of sequencing of layers of different resistivity. The difference in ρ_a values at the lower layer given by EC is less compared to that at the interface given by D'B e.g. in Figure 9 the value of D'B is 1.001 $\times 10^9$ Ohm.cm as compared to EC value of 8.79×10^7 Ohm.cm.

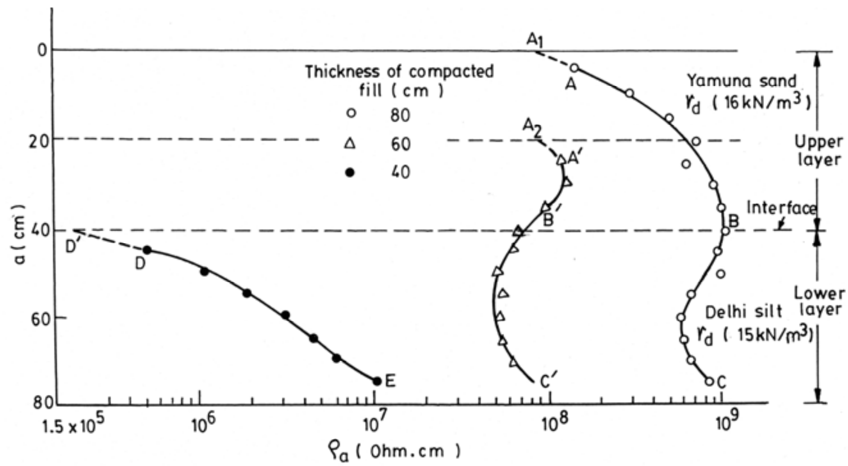

Fig. 9 Variation of ρ_a with a for Yamuna Sand (γ_d = 16 kN/m^3) Overlying Delhi Silt

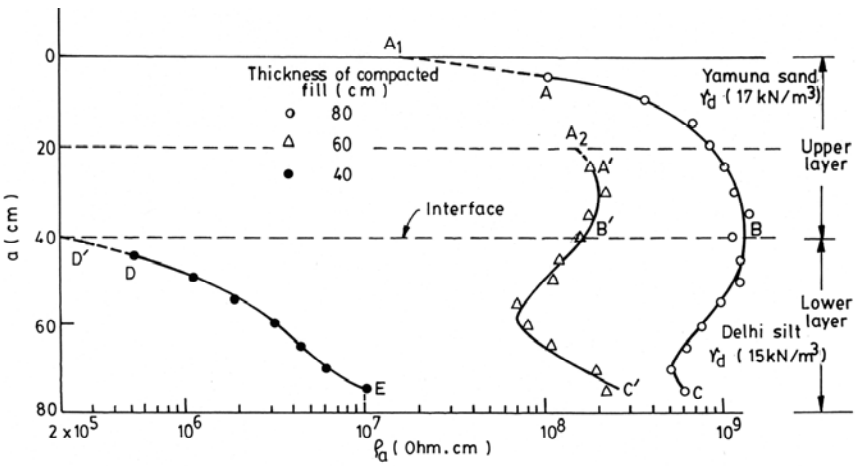

Fig. 10 Variation of ρ_a with a for Yamuna Sand (γ_d = 17 kN/m^3) Overlying Delhi silt

The apparent resistivity as a function of electrode spacing for different γ_d of Yamuna sand is presented in Figure 11. At any given electrode spacing, the curves in Figure 11 show increase in γ_d. It is also seen that for any particular γ_d, the resistivity increases up to the interface and below interface it starts decreasing as the current penetrates down. The combined effect on ρ_a below interface in this case is more pronounced by low resistivity layer as the depth of current penetration increases in it.

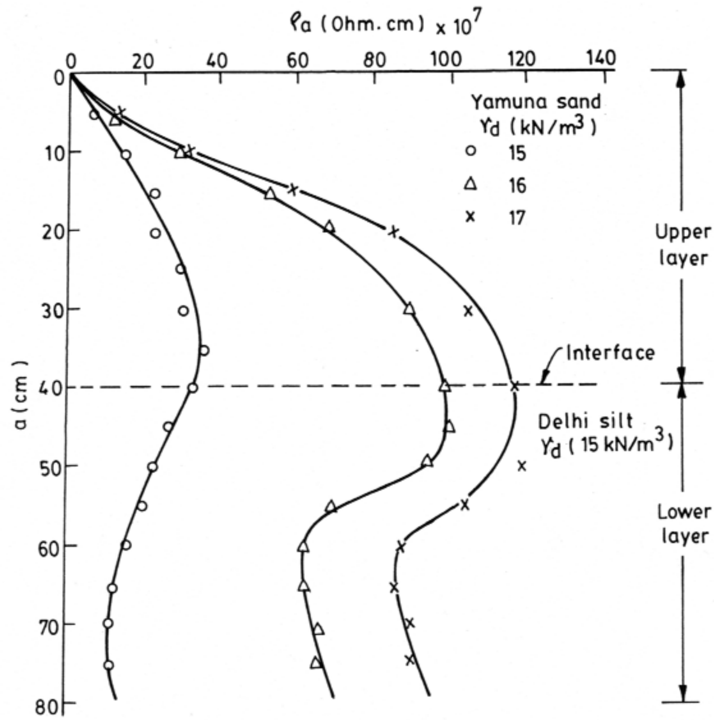

Fig. 11 Apparent Resistivity as a Function of Electrode Spacing for Yamuna Sand

Layers of same unit weight

Experiments have been conducted on two Layer soil system with both the soils compacted at same unit weight of 15 kN/m^3. In these studies each soil layer was compacted up to a total thickness of 40 cm and the layer sequence was also altered (i.e. from $\rho_1 < \rho_2$ to $\rho_1 > \rho_2$). The Figures 12 and 13 illustrate the variation between electrode spacing and resistivity for $\rho_1 < \rho_2$ and $\rho_1 > \rho_2$ respectively. In addition to curves ABC, A'B'C' and D'DE, the curves MN and QU have been introduced in these Figures. The curves MN and QU show the variation between electrode spacing and resistivity for top and bottom layers respectively and represents the values of corresponding soil when compacted as a single layer at the same unit weight. Thus curve QU gives resistivity values for the bottom layer eliminating the effect of overburden.

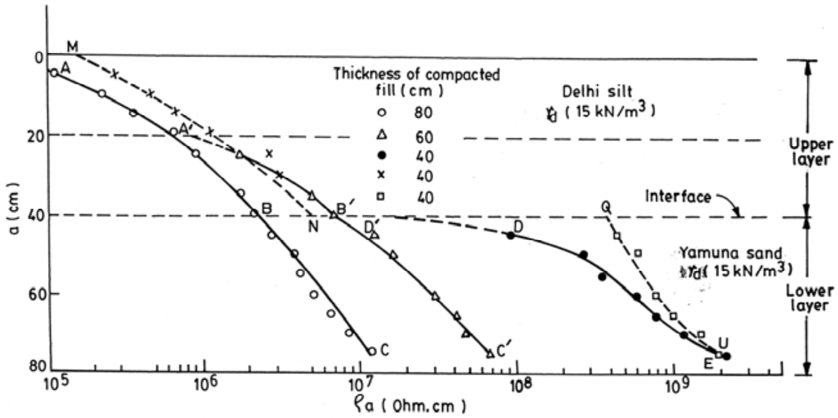

Fig. 12 Variation of ρ_a with a for Delhi Silt overlying Yamuna Sand

It can be seen from Figure 12, which represents Delhi silt overlying Yamuna sand that the curves AB and MN exhibit nearly the same trend with marginal differences in electrical resistivity. The curves D'DE and QU when compared show significant differences at the interface, whereas the difference in resistivity decreases as the current penetrates deeper, finally the points E and U almost merge at the bottom. The curves BC and B'C' demonstrate the combined effect of resistivity of both the soils. Similar inferences can also be drawn from Figure 13, which corresponds to layer sequence of Yamuna sand overlying Delhi silt.

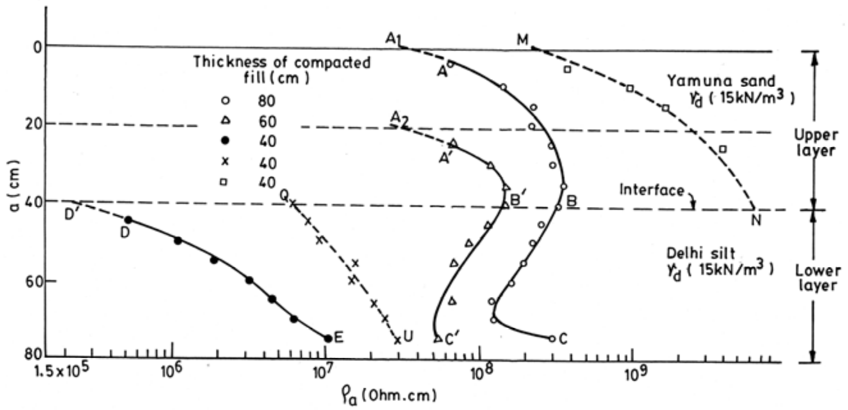

Fig. 13 Variation of ρ_a with a for Yamuna Sand overlying Delhi Silt

It is evident from the above observations that as long as electrode spacing, i.e. the depth of current penetration is smaller than the thickness of the top layer, the electrical resistivity values display no effect of the presence of bottom layer. As soon as the electrode spacing exceed the thickness of top layer the effect of the presence of bottom layer is significantly reflected on the electrical resistivity values. Depending upon the ratios of ρ_1 and ρ_2 and the depth of current penetration beneath interface, the values of apparent resistivities change e.g. in Figure 12 for the case of $\rho_1 < \rho_2$, the ρ_a values beneath interface are definitely higher than ρ_1 but lower than ρ_2 and varies with depth below interface. Similarly a reverse trend of ρ_a can be noticed in Figure 13, wherein $\rho_1 > \rho_2$.

The experimental results shown in Figures 3 and 4 for single layer soil system, Figures 5, 6, 7 and 12 for low resistivity layer overlying high resistivity layer and Figures 9, 10 and 13 for high resistivity layer overlying low resistivity layer clearly demonstrate the dependence of ρ_a on *a*, ρ_1, h_1, ρ_2, h_2 and so on as governed by Equations (1) and (2).

Comparative Study of Interpretation Techniques

Herein an attempt has been made to interpret the present laboratory resistivity soundings data obtained under controlled conditions of testing and compare with the actual values. The results obtained in the laboratory for single layer and two layer soil system with both the soils compacted at γ_d of 15 kN/m^3 have been interpreted using Moore with Hummel's extension, Direct slope, Inverse slope, Barnes Layer and Master curve matching techniques. The interpreted values of resistivities (ρ_i) and thicknesses (t_i) thus obtained are presented in Table 2. In order to facilitate comparison of these values with actual (experimentally determined) true resistivities (ρ) of soils, the ρ values from Table 1 are reproduced in the last column of Table 2 along with actual layer thicknesses (*t*).

A comparative study of these graphical techniques in terms of the actual and interpreted values of thickness and resistivity of layers is summarized in the following sections.

***Layer thicknesses*:** The values of t_i from Moore with Hummel's extension are in close agreement followed by Barnes layer with the actual thicknesses (*t*). The former provides an accuracy of t_i within $\pm$ 5% whereas, the latter within $\pm$ 7.5%.

The remaining techniques exhibit large deviations between t_i and *t*. These deviations are of the order of $\pm$ 20% and $\pm$ 25% for Master curve and Inverse slope techniques respectively. The Direct slope technique invariably provides significantly less thicknesses than the actual, with the deviation of around (-) 30%.

***Layer resistivity*:** The values of ρ_i from Barnes layer compares reasonably well with the actual ρ followed by Master curve technique. There is a marginal deviation between ρ and ρ_i obtained from Moore with Hummel's extension. Both Direct slope as well as Inverse slope techniques provide ρ_i , which significantly deviates from ρ.

Table 2: Comparison of Layer Thicknesses and Resistivities by Different Interpretation Techniques

Soil Layer System	Moore with Hummel's Extension		Direct Slope		Inverse Slope		Barnes Layer		Master Curves		Experimental (actual)	
	t_i (cm)	ρ_i (Ohm.cm)	t_i (cm)	ρ_i (Ohm.cm)	t_i (cm)	ρ_i (Ohm.cm)	t_i (cm)	ρ_i (Ohm.cm)	t_i (cm)	ρ_i (Ohm.cm)	t (cm)	ρ (Ohm.cm)
Single Layer	19	2.1×10^6	16	5.9×10^5	23	6.1×10^6	18	9.8×10^5	23	8.7×10^5	20	1.02×10^6
(Delhi Silt)	41	6.3×10^6	34	9.1×10^5	46	1.2×10^7	43	3.7×10^6	44	4.5×10^6	40	4.10×10^6
	62	8.9×10^6	53	6.3×10^6	57	8.7×10^7		1.4×10^7	58	1.2×10^7	60	9.60×10^6
	-	3.7×10^7	-	8.9×10^6	-	9.4×10^7	-	2.9×10^7	-	3.8×10^7	80	2.10×10^7
Single Layer	19	6.1×10^7	14	9.2×10^6	25	5.6×10^8	18	5.4×10^7	24	9.3×10^7	20	8.30×10^7
(Yamuna Sand)	39	3.6×10^8	32	3.8×10^7	47	9.3×10^8	42	3.6×10^8	38	1.6×10^8	40	2.80×10^8
	61	5.7×10^8	56	5.9×10^7	69	2.2×10^9	63	8.7×10^8	65	7.7×10^8	60	5.90×10^8
	-	9.3×10^8	-	8.5×10^7	-	6.3×10^9	-	1.6×10^9	-	1.3×10^9	80	8.20×10^8
Two Layer (Delhi	21	2.9×10^6	15	4.8×10^5	23	7.2×10^6	18	2.3×10^6	22	5.1×10^6	20	1.02×10^6
silt over Yamuna	41	5.8×10^6	33	8.8×10^5	44	2.9×10^7	39	5.1×10^6	43	9.4×10^6	40	4.10×10^6
sand)	58	6.9×10^7	51	9.2×10^6	57	8.9×10^8	63	9.6×10^7	66	1.6×10^8	60	8.30×10^7
	-	4.3×10^8	-	3.9×10^7	-	9.1×10^8	-	5.7×10^8	-	8.7×10^8	80	2.80×10^8
Two Layer	21	7.2×10^7	17	8.8×10^6	17	3.2×10^8	19	4.9×10^7	25	5.2×10^7	20	8.30×10^7
(Yamuna sand	42	4.5×10^8	35	5.2×10^7	36	8.9×10^8	42	4.3×10^8	45	8.6×10^8	40	2.80×10^8
over Delhi silt)	59	3.1×10^6	56	8.7×10^5	64	2.3×10^7	62	9.9×10^5	63	8.9×10^5	60	1.02×10^6
	-	8.3×10^6	-	9.9×10^5	-	5.9×10^7	-	5.2×10^6	-	7.2×10^6	80	4.10×10^6

The assessment of these interpretation techniques in general indicates that each one is associated with certain limitations to provide the values of either layer thickness or its resistivity or both, which are comparable with the actual. However, in comparison, Barnes layer method more or less furnishes both these parameters reasonably close to the actual.

Conclusions

On the basis of laboratory model studies on electrical resistivity of dry soils under controlled conditions following conclusions have been summarized.

The soils as a single layer or two layer system exhibit increase in resistivity with increase in initial compaction dry unit weights. This has been noticed at all the depths of current penetration.

In a two layer soil system, the values of apparent resistivity remain almost the same as that of true resistivity for top layer as long as the depth of current penetration does not exceed the thickness of top layer. However, as the depth of current penetration exceeds the thickness of top layer, the apparent resistivity values tends to exhibit the combined effect as a function of true resistivities of each of the layer, the thickness of top layer and the depth of current penetration beneath the interface (within bottom layer). The combined effect is more pronounced by the resistivity of lower layer (relative to upper layer as $\rho_1 < \rho_2$ or $\rho_1 > \rho_2$).

Within the practical limits Barnes layer technique appears to be reasonably acceptable to derive true resistivity and thickness of layers as compared to all other graphical interpretation techniques studied here.

Notations

a	=	Electrode separation (Wenner); Half the spacing between current electrodes (Schlumberger)
a_1, a_2, a_n	=	Electrode separations
b	=	Half the spacing between potential electrodes (Schlumberger)
C_1, C_2	=	Current electrodes
E	=	Potential drop
h_1, h_2, h_i, h_{n-1}, h_n	=	Thicknesses of strata
$\bar{h}_n$	=	Part thickness of n^{th} stratum
I	=	Current
J_1	=	Bessel's function
K	=	Kernel function
ML	=	Silt with low plasticity
m	=	Dummy variable
P_1, P_2	=	Potential electrodes
R	=	Resistance

t, t_1, t_2, t_3	=	Thicknesses of layers
t_i	=	Interpreted layer thickness
γ_d	=	Dry unit weight
ρ, ρ_1, ρ_2, ρ_i, ρ_n	=	True resistivity of layers
ρ_a, $\rho_{a1}, \rho_{a2}, \rho_{an}$	=	Apparent resistivity of layers
ρ_i	=	Interpreted true resistivity

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