ELECTRICAL RESISTIVITY TOMOGRAPHY IN GEOTECHNICAL ENGINEERING APPLICATIONS

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Abstract. Characterization of subsurface soil is essential for foundation design of important civil engineering structures. In conventional geotechnical investigation the soil profiling and their characterization is done by collecting samples from the field either through open pit sampling or through boring and then performing laboratory test for their classification and determination of strength and compressibility characteristics. In-situ methods like Standard Penetration Test (SPT), Cone Penetration Test e.g. static (SCPT) and dynamic (DCPT), Pressure Meter Test (PMT) and Dilato-Meter Test (DMT) are also available. But these methods are time consuming and costly. If vast tracts are to be investigated for preliminary exploration then Geophysical methods can aid to collect information about the subsoil conditions. Geophysical methods allow to measure physical properties like electrical resistivity, seismic wave velocity, electrical permittivity, magnetic intensity etc. These observations can be used for surveying large tracts or ancient structures composed of dissimilar materials. Apart from these some problems that vex the civil engineers is significant increase in the permeability of desiccated soils due to cracks in these soils due to shrinkage. Such a situation may lead to the progressive failure in flood embankments. Geophysical methods have great potential to aid archaeological investigation in identifying archeological features in unexcavated areas. Electrical Resistivity Tomography (ERT) is very commonly applied in such studies because of its adaptability in identifying walls, cavities etc. at different depths.

The paper pertains to the potential of application of ERT in geotechnical and archaeological investigation providing an overview and its use in subsoil profiling and detection of foundation details of old structures. The power of the method in identifying the hidden features of buried objects and subsurface profiling has been demonstrated with examples.

Keywords: Electrical Resistivity, Tomography, soil characterization, geophysical exploration methods

1 Introduction

For successful design and construction of civil engineering infrastructures, it is essential to undertake Geotechnical investigation to find out the nature, extent and engineering properties of soils at the site. Such investigations are generally done by digging boreholes at different location at the site extending the same up to the desired depths for collection of soil sample

from different depths. The various methods for extending such boreholes are use or trial pits, shafts and headings, percussion boring, mechanical augers, hand portable augers, wash borings, rotary drilling. Position of the ground water table is also determined during the boring process. The collected soil samples can be divided into two main categories, undisturbed and disturbed. Undisturbed samples are required mainly for shear strength and compressibility characteristics, which are obtained by using techniques preserving the in-situ soil-structures and moisture content of the soil. On the other hand disturbed sample are used for classification purpose only

Alternatively in-situ tests for Geotechnical investigation have also been devised. Commonly used techniques are as follow:

- Plate load test
- Standard penetration test
- Dynamic cone penetration test
- Static cone penetration test
- Pressure-meter test
- Dilatometer test.

Each of the above tests has their merits and demerits. However, standard penetration test is most widely used all over the world. Specific correlations have been developed for each of these methods by several investigators to interpret and use the observed data for classifying in the soil strata and engineering properties. For conducting these test at the site needs lot of planning, time and money. Some time it become very large with respective to the total budget of the project.

In order to circumvent such difficulties development of alternative methods are required.

'In 1912 Conrad Schlumberger conducted the first geoelectrical resistivity experiment in the fields of Normandy. Around 1915, a similar idea was developed by Frank Wenner in the United State of American (Kunetz, 1966) **[1]**. The classical methods of geoelectrical resistivity surveys have undergone significant changes in the last four decades. Data acquisition was more or less carried out manually till the 1980s, which is labour intensive and slow, and the quality of the measured data might be of poor quality. Initially, multi-electrode systems with manual switching (Barker, 1981)**[2]** were used before the emergence of computer-controlled multi electrode systems with automatic measurements and data quality control, which has tremendous impact on the quality of the data and the speed with which they are collected. When adequate computers became widely available the inverse problem of ERT could be solved numerically, and the work of Loke and lane (2004)**[3]** at Birmingham University was among the first such solution, and their approach is still widely used.'

Recently geoelectrical resistivity survey in the area of archaeology and geotechnical engineering have been reported, Abu-Zeid 2006**[7],** Ganiyu, (2006) **[4].** They have done Investigation of Soil moisture content over a cultivated farmland in Abeokuta Nigeria using Electrical Resistivity Methods and Soil Analysis. Constantin et al. (2003)**[5],**Zhou et al. (2001)**[6],** Abu-Zeid et al.(2005)**[7],** Sudha et al. (2008)**[9]** used ERT in subsurface soil characterization. They correlated soil resistivity with Standard Penetration Test resistance number. This study opens the avenue to estimate bearing capacity of foundations. Thus determination of soil strength from ERT results can be very effective.

In India application of these methods are in initial stage and not much expertise is available therefore an initiative of undertaking research in the area is warranted. The main aim of this

paper to present a case study for characterisation of the subsurface soil through application of ERT.

1.1 **Brief review of available geophysical exploration techniques**

Different Geophysical exploration method like seismic reflection and refraction technique, electrical resistivity method, magneto telluric method etc. are available of geophysical perspective, however these method are used in different fields cutting across in various disciplines in science and engineering.

Advantages of these methods are exploration can be covered in wider area in lesser time and expense, and these techniques are non-invasive.

The imaging of the soil lying below the ground surface is based on the collection of data pertinent to the methodology used. The anomaly like presence of ground water, soil stratification, presence of rock, faults, joints and fissures and their extent can be interpreted easily from their tomographic imaging. In this respect geophysical exploration techniques score over the geotechnical techniques in site investigation procedures as described above. But it should be noted that these methods gives approximate idea about the subsurface conditions. However, adoption of such procedures help the civil engineers in taking quick decision for site selection and planning the next stage of geotechnical investigation, saving plenty of money, time and energy.

Seismic methods: These methods are based on the principles that elastic shock waves moves at different velocities in different materials. At the interface of the two different strata of different materials, the elastic stress waves are partly reflected and partly refracted. There are two types of body waves namely the compression waves (P-waves) and shear waves (S-waves). In the compression waves the direction of the movements of the particles coincides with the direction of propagation. The shear waves can be separated into two components: (1). SV-waves in which the motion of particles is in the plane of propagation and (2). SH-waves where in the motions of the particles is perpendicular to the plane of propagation. If a P-wave impinges on the boundary between two layers, there will be two reflected waves and two refracted waves. These waves follow certain laws. These are available in standard text books (Das and Ramana, 2011; Kolsky, 1963)

This method can be adopted by using a single geophone and producing a series of detonations or impacts at increasing distance from geophone. Then arrival time is plotted against the distance between the source and the geophone. From this plot the velocities of the direct wave and the refracted wave can be estimated. The general types of soil and rock can be determined from knowledge of these velocities. Typical values are as follows:

Table 1 Speed of velocity in different type of rock and soil

Types of rock/ soil	Granite	Sand stone	shale	Hard clay	Loose gravel (wet)	Loose sand (wet)	Loose sand (dry)
Velocity (m/sec)	4000-6000	1500-3000	1300-3000	600-1500	500-1000	500-1500	250-600

Magneto telluric (MT) Method: It refers to a technique in which electrical resistivity is determined by making measurements of electric and magnetic fields related to naturally occurring currents ("telluric", caused mostly by lightning strikes) flowing in the ground. The MT theory, along with appropriate data inversion procedures, allows the determination of the resistivity distribution in the subsurface, on depth scale ranging from a few tens of meters to hundreds of kilometers. Magnetic data can also collect aerially using either a light helicopter or aero plane by Magnetometer mounted on it.

Gravimetric Method: It is a potential field technique which measures variations in the Earth's gravitational field. These variations are caused by density contrasts in the near surface rock and sediment. Gravimetric surveys are carried out using extremely sensitive instruments capable of measuring tiny variations in the gravitational field. Instruments for measuring gravity are called gravity meters or gravimeters

Electrical resistivity tomography (ERT): It is one of the most important Geophysical tool for imaging the shallow subsurface soil and for characterization of soil for making the soil profile. Electrical Resistivity method is also one of the methods mostly used in archaeological geophysics, as well as in engineering geological investigations. its other applications are characterize subsurface hydrogeology, determine depth of bedrock/overburden thickness, determine depth of groundwater, map stratigraphy, map clay aquitards, map salt-water intrusion, map vertical extent of certain types of soil and groundwater contamination, estimate landfill thickness. With the help of software (like RES2DINV and RES3DINV) we can create 1D, 2D and 3D image of the anomaly. Among all the methods as described above Electrical resistivity is simplest of all the method as described and easy to perform.

The method depends on differences in electrical resistance of different soils and rock types. The flow of current through soil is primarily due to electrolytic action and therefore depends on concentration of dissolved salts in pore water: the mineral particles of a soil are poor conductors of current. The resistivity of soil therefore decreases with increasing water content and concentration of salt. Dense sands above the water table would show high value of resistivity due to low degree of saturation and lack of the presence of dissolved salts. Saturated clay having high void ratio would exhibit low value of resistivity due to relative abundance of pore water and free ions in the pore water. For ERT four electrode are arranged in a manner in which Direct current (DC) or low frequency alternating current (AC) of known magnitude introduce in ground using a pair of current electrode at one point and measure the potential deference at potential electrode in terms of resistivity (ohm).After calculating the apparent resistivity (ohm-m) and compare the apparent resistivity of soil with the standard resistivity of soil we can characterize the soil. Different types of soil composition have different resistivity value so that it is easy to characterize the soil at different location under the ground surface. Typical values of resistivity of different types of soils/rocks are as follows:

Table 2 Resistivity of different type of soil and rock

Type of rock/soil	Sound rock	Weathered rock	Gravel	Sand	Clayey sand	Saturated clay and silt
Resistivity (ohm-m)	>5000	1500-2500	1500-4500	500-1500	200-500	2-100

Apparent resistivity represents the weighted average of true resistivity in a large volume of soil, the close to the surface being more heavily weighted than the soil at depth. Presence of a

stratum of oil of high resistivity lying below a stratum of low resistivity forces the current to flow closer to the surface, resulting in higher values of apparent resistivity. The opposite is true if a stratum of low resistivity lies below a stratum of high resistivity.

Electrical resistivity tomography (ERT) is one of the most commonly applied techniques of Geophysical surveying. The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated (Loke, M.H. (2004) *Tutoria*l)**[8]**. The aim of ERT is to scan the subsurface along the survey line using a selected array

2 Soil characterization

2.1 Experimental procedure

For lateral and vertical profiling of soil using resistivity technique, Resistance (ohm) is calculated in the field using any of the Wenner method Fig**. 5** and Schlumberger method Fig**. 6**, using Instrument SSR MP-1. In these methods four electrodes are use in which inner electrodes are potential electrodes and outer electrodes are current electrode. DC (direct current) is applied at the current electrodes and potential difference is measured at potential electrodes. Difference between Wenner and Schlumberger method is only about spacing between the electrodes. In Wenner method the electrodes are equally spaced but in Schlumberger method spacing between the current electrodes is three times the spacing between the potential electrodes.

In Fig. **1**, a schematic diagram of the arrangement of the model blocks and apparent resistivity data points is shown. The data points are designated as x and its spatial locations in a two dimensional Cartesian frame of reference (designated as x and y) is also shown in this figure. Layers are numbered as 0, 1, 2,…..as shown.

For measuring resistance for layer 1 the spacing is maintained as 1m between all the electrodes taking ‘0’ as the reference. It means that the current electrode is placed at 0 and 3 and putting the potential electrode at 1 and 2. After measuring the resistance at that location, all the four electrodes are moved by 1m in the y direction increasing the value of n by 1 unit up to the layer 6; For layer 7 and 8 the spacing between potential electrodes are kept as 2 meter along with n value 4 and 5. Following the above procedure resistance is measured at all the data points.

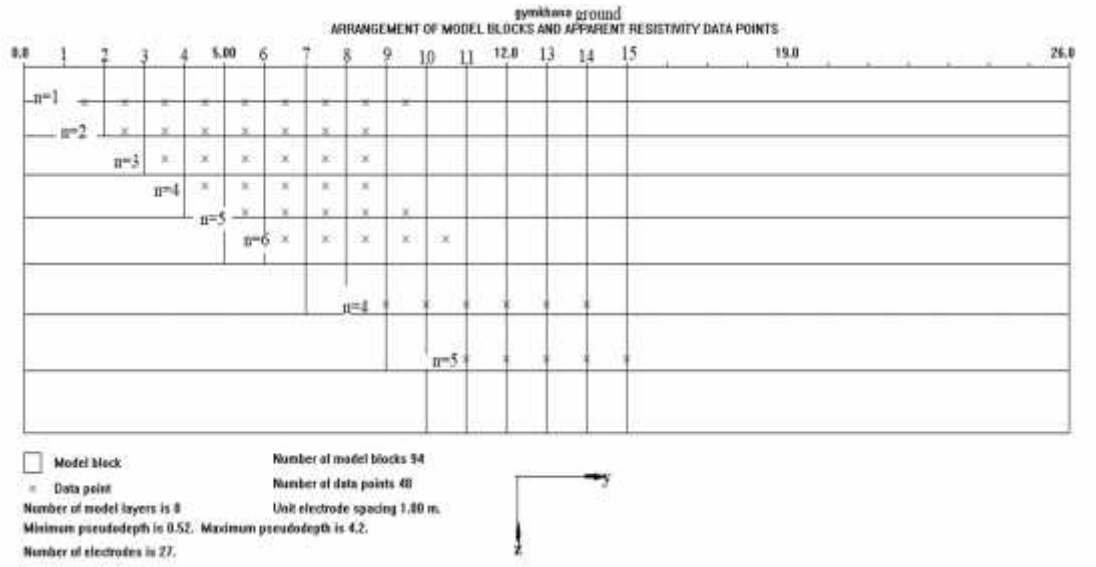

Fig. 1. Model block and apparent Resistivity data point

A location was chosen near the Gymkhana ground, IIT (BHU) and its co-ordinates were obtained with the help of a GPS. Remotely sensed photograph of the site with the marked point is shown in Fig. **2**. Fig.**3**, shows the soil profile with the apparent resistivity inversion obtained using RES2DINV software. It extends up to 15 meter in y-direction and 4.88 meter in z-direction. From the diagram it is seen that the measured resistivity of soil at the site lies in the range of 50 ohm-m to 210 ohm-m; comparing the values with the standard resistivity of soil (Table **2**) and the soil extending over the zone is identified as clayey sand. But for the soil lying between 3.96 m to 4.88 m depth have high resistivity values ranging from 490 ohm-m to 750 ohm-m and comparing these values with standard values it is inferred that soil type should be silty sand with the possibility of the presence of some gravel packet within the strata.

Fig. 2.Location of resistivity data point (coordinate:25.259581, 82.988533)

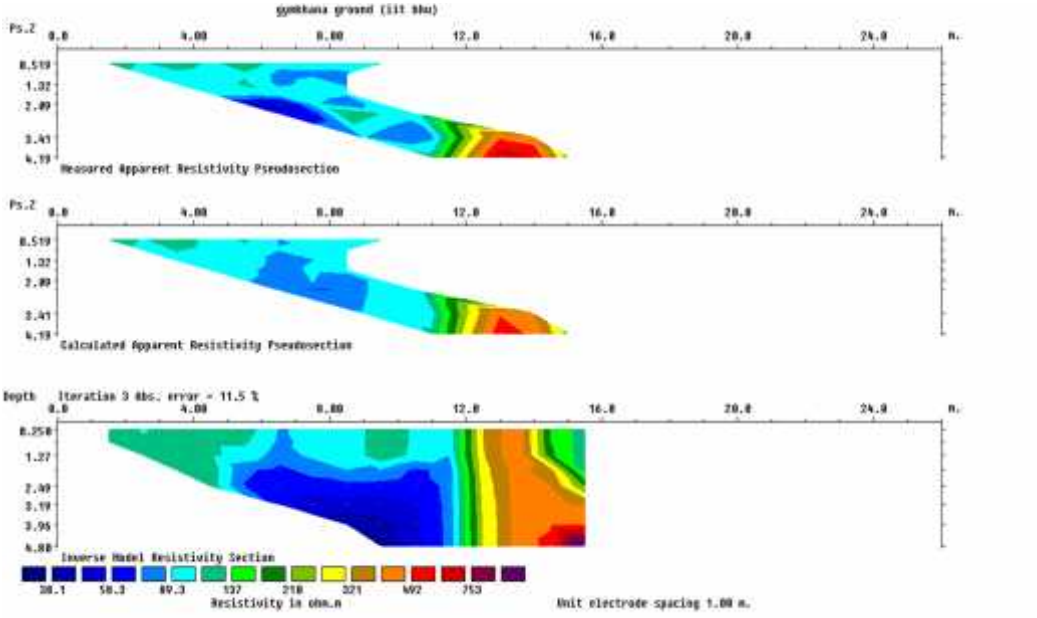

Fig. 3. Soil profile apparent resistivity inversion

2.2 **Observation made and interpretation of data**

To verify whether the inferred soil profile from the measured resistivity data is correct or not, grain size classification was made conducting sieve analysis following Indian Bureau of Standards in geotechnical engineering laboratory at IIT BHU Varanasi.

Soil samples from an arbitrary depth 1meter were collected and the test was conducted taking 1Kg of soil. The sieve test results are presented in the (Table **3**).

Table3: Sieve test results

Sieve size	Wight retain(gram)	% weight retained	Remark
2mm	222	22.2	Well graded sand
1mm	311	31.1	
475	230	23	
250	89	8.9	
150	44	4.4	
75	50	5	
pan	40	4	Mixture of silt and clay

Grain size classification of the collected soil sample as specified by Indian standard soil classification system (ISSCS) as presented in Table **4**, has been made and the type of soil as obtained from the test is included under the remark column of Table3. Thus the different constituents of the soil at the depth of 1 meter are:

Sand: Coarse: 22.2% , Medium: 54.1%, Fine:18.3%
Silt and clay: 4%

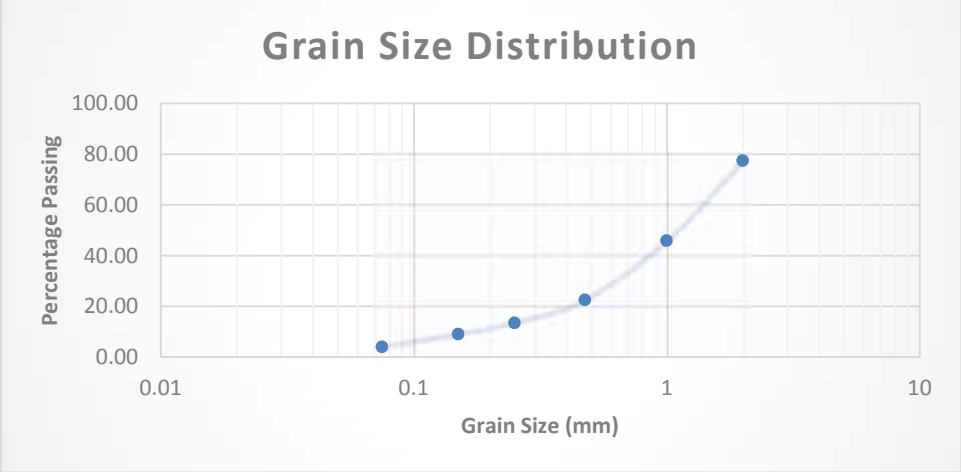

Fig. 4.Grain size distribution curve

From the curve (fig.**4**), D10, D30 and D60 can be calculated, these value are:
D10 = 0.16954, D30 = 0.6411, D60 = 1.4457
$C_u = \frac{D_{60}}{D_{10}}$, and the value is 8.5271
$C_C = \frac{D_{30}^2}{D_{60} * D_{10}}$, and the value is 1.6768

From the result analysis it can be seen that the soil is SW (well graded sand) according to Indian standard soil classification system, for SW,C_u should be greater than 6 and C_C should be between 1 and 6.

The soil as classified at that depth from electrical Resistivity technique (ERT} is clayey sand. As per ISSCS classification the soil passing through 75 « sieve is fine grained and is classified either as silt and clay depending on its plasticity value, which is not possible from ERT test. Thus the prediction as made by ERT is fairly close to the classification based on direct measurement.

Thus it can be concluded that the predictions are close to the nature of soil at the ground. Similarly soils from different depths are collected and categorized and the predicted soil variation with depth is found to be fairly accurate.

Table 4: Classification of soil as per Indian Standard (ISSCS)

Very coarse soil	Boulder size		>300 mm
	Cobble size		80-300 mm

Coarse soil	Gravel	Coarse	20-80 mm
		Fine	4.75-20 mm
	Sand	Coarse	2-4.75 mm
		Medium	0.425-2 mm
		Fine	0.075-0.425 mm
Fine soil	Silt		.0002-0.075 mm
	Clay		< 0.002 mm

Fig. 5.Wenner array arrangement

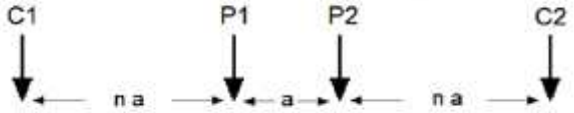

Fig. 6.Schlumberger array arrangement

Following the above procedure the following cases were also taken up: Determination of the extent of the foundation of an wall, Foundation depth of the Rajputana hostel (which is about 100 years old), extent of root zone of a tree and finally determination of the depth of the ground water table. All these are significance from civil engineering profession. As investigating foundations of ancient structures involves time, money and elaborate procedure for getting permission to do so, even though it was the initial objective of the paper, instead of a very ancient structure investigation were carried out to explore the extent of a structure more than 100 years old with remarkable success. The method can be easily extended to ancient structure. However, these studies have not been reported here for reasons of space and brevity.

3 Conclusion

The Characterisation of the subsurface soil has been carried out in IIT BHU campus, India with application of Electrical resistivity method. The Resistivity value is correlated with the sieve analysis and grain size distribution result obtained in Geotechnical lab.IIT BHU. The calculated value of Cu= 8.5271 and Cc=1.6768 of the soil from the study area in the laboratory is similar to the field result through ERT It is also concluded that the Schlumberger array arrangement give good result for deep soil body as compare to the Wenner array arrangement. For getting the high accuracy in ERT, required to take minimum electrode spacing. In other problems like the extent of foundation of an wall and 100 year ols structure, determination of the extent of root zone of a tree having direct bearing on studying

the foundations of ancient structure has also been applied successfully. For reasons of space and brevity these are not presented here.

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