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Soil characterization using electrical resistivity tomography and geotechnical investigations

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ABSTRACT

Electrical Resistivity Tomography (ERT) has been used in association with Standard Penetration Test (SPT) and Dynamic Cone Penetration Test (DCPT) for Geotechnical investigations at two sites, proposed for thermal power plants, in Uttar Pradesh (UP), India. SPT and DCPT tests were conducted at 28 points and two ERT profiles, each measuring 355 m long, were recorded using 72 electrodes deployed at 5 m spacing. Electrical characterization of subsurface soil was done using borehole data and grain size analysis of the soil samples collected from boreholes. The concept of electrical resistivity variation with soil strength related to the grain size distribution, cementation, porosity and saturation has been used to correlate the transverse resistance of soil with the number of blow counts (*N*-values) obtained from SPT and DCPT data. It was thus observed that the transverse resistance of soil column is linearly related with the number of blow counts (*N*-values) at these sites. The linear relationships are site-specific and the coefficients of linear relation are sensitive to the lithology of subsurface formation, which was verified by borehole data. The study demonstrates the usefulness of the ERT method in geotechnical investigations, which is economic, efficient and less time consuming in comparison to the other geotechnical methods, such as SPT and DCPT, used for the purpose.
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1. Introduction

Characterization of subsurface soil and determination of soil strength are prerequisite for the foundation design of important civil engineering structures. Electrical characterization of soil was done by conducting surface electrical resistivity measurements and subsequently translating these data in terms of electrical properties of subsurface soil (Israil and Pachauri, 2003). Various attempts have been made in literatures to integrate the ERT and geotechnical data for characterization of subsurface soil (Cosenza et al., 2006; Gay et al., 2006). The application of electrical resistivity for characterization of soil was reviewed by Samouëlian et al., (2005).

Alternatively, in geotechnical studies, Standard Penetration Test (SPT) furnishes data about the resistance of soils to penetration, which can be used to evaluate the soil strength in terms of number of blows (*N*-values). The *N*-values are defined as the number of blows per 30 cm of penetration into the soil. Following the procedure of IS 6403 - (1981) code, *N*-values can be used to obtain the bearing capacity of soils. In Dynamic Cone Penetration Test (DCPT), the resistance, *N*-value, to penetration of the cone in terms of the number of blows per 30 cm of penetration is correlated with the bearing capacity of the soil. The data from these geotechnical tests (SPT and DCPT) in association with the borehole data and laboratory measurement of soil properties (e.g., grain size distribution, degree of saturation and permeability) are used to characterize the subsurface soil.

Geotechnical tests are time-consuming and expensive. On the other hand, geoelectrical methods are faster and comparatively cheap. The use of Electrical Resistivity Tomography (ERT) technique provides the electrical image of subsurface soil and has become an important tool for the electrical characterization of soil. Correlation between electrical parameters and soil strength, derived from geotechnical tests, can be studied by choosing different electrical parameters. It has been reported in literature (Braga et al., 1999; Giao et al., 2003) that the relationship between the electrical parameters such as chargeability, resistivity and *N*-values is poor.

The physics of electrical current flow in the subsurface soil suggests that the possible relationship between the soil strength and electrical resistivity should be based on the parameters which control soil strength as well as electrical resistivity such as grain size distribution, degree of saturation, porosity and cementation. It is so since resistivity is sensitive to the salinity of saturating fluid whereas soil strength is not related with it. Therefore, the relationship between electrical parameters and soil strength will be meaningless if the salinity of saturating fluid changes with depth. On the other hand, clay content in soil matrix can affect both soil strength as well as its

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resistivity with different degree. The ion exchange property of clay forms a mobile cloud of additional ions around each clay particle. These ions facilitate easy flow of electrical current. Thus, in fine-grained soils such as clay, electrical resistivity is always lower than expected on the basis of chemical analysis of water extracted from the soil (Zhdanov and Keller, 1994). Therefore, clay content in the soil may change relationship between electrical parameter and soil strength.

In the present paper, we will report our investigations on two locations having different soil matrix for soil characterization by conducting ERT, SPT, DCPT and laboratory measurements. The sites were proposed for thermal power plant and are located in Aligarh and Jhansi in Uttar Pradesh (UP), India. The locations of these sites along with points of investigation and ERT profile line are shown in Fig. 1. The derived electrical resistivity values are first calibrated with the borehole data of subsurface soil, and subsequently used to compute transverse resistance, which is correlated with the N-values recorded from geotechnical tests at each site.

2. Field investigation

The field investigations comprise of geoelectrical investigations using Electrical Resistivity Tomography (ERT) technique and geotechnical investigations, which include SPT, DCPT tests and grain size distribution of soil samples collected from these locations. Borehole data were used for calibration and correlation of resistivity values to the subsurface soil. The details of field investigation are discussed in the following:

2.1. Geoelectrical investigations

Electrical Resistivity Tomography (ERT) survey was carried out using multi-electrode system (Syscal Junior). The data were recorded using Schlumberger–Wenner sequence with 72 electrodes deployed along the profile line at an inter-electrode spacing of 5 m. The total length of each profile line was 355 m. Processing and inversion of resistivity image profile data were performed using RES2DINV code (Loke and Barker, 1996; Loke, 1997). For each data sets, L_1 norm was used for the data misfit and the inversion was carried out using the L_1 norm (blocky) inversion method for the model roughness filter (Loke et al., 2003). The method uses a finite difference scheme for solving the 2-D forward problem and blocky inversion method for inverting the processed ERT data. RES2DINV generates the inverted resistivity depth image for each profile line. The quality of inversion result was checked by monitoring absolute error (e_{rms}) between the measured and predicted apparent resistivity given by,

$$e_{\mathrm{rms}} = \sum_{i=1}^{N} \left[\frac{\left| \log\left(\rho_{a_{i_{\mathrm{meas}}}}\right) - \log\left(\rho_{a_{i_{\mathrm{calc}}}}\right) \right|}{N} \right] \quad (1)$$

where $\rho_{a_{i_{\mathrm{meas}}}}$ and $\rho_{a_{i_{\mathrm{calc}}}}$ are the measured and calculated apparent resistivity values at ith data point respectively and N is the total number of data points.

Geophysical inversion suffers from non-uniqueness. One way to reduce non-uniqueness is to use additional data/information from other sources to constrain geophysical inversion. We used borehole data to limit the resistivity values within the acceptable range for different lithological formations. RMS values of 9% and 6% for the two investigated sites indicate that the data are fitted with the computed response and the average error floors are 9% and 6% in the data at Aligarh and Jhansi, respectively. In the present investigation, SPT and DCPT data were recorded up to 16 m depth, therefore, the resistivity model is restricted to a depth of 24 m. Inverted resistivity-depth models are shown in Fig. 2 (a and b) for Aligarh and Jhansi, respectively. Resistivity distribution of subsurface soil in these areas shows a

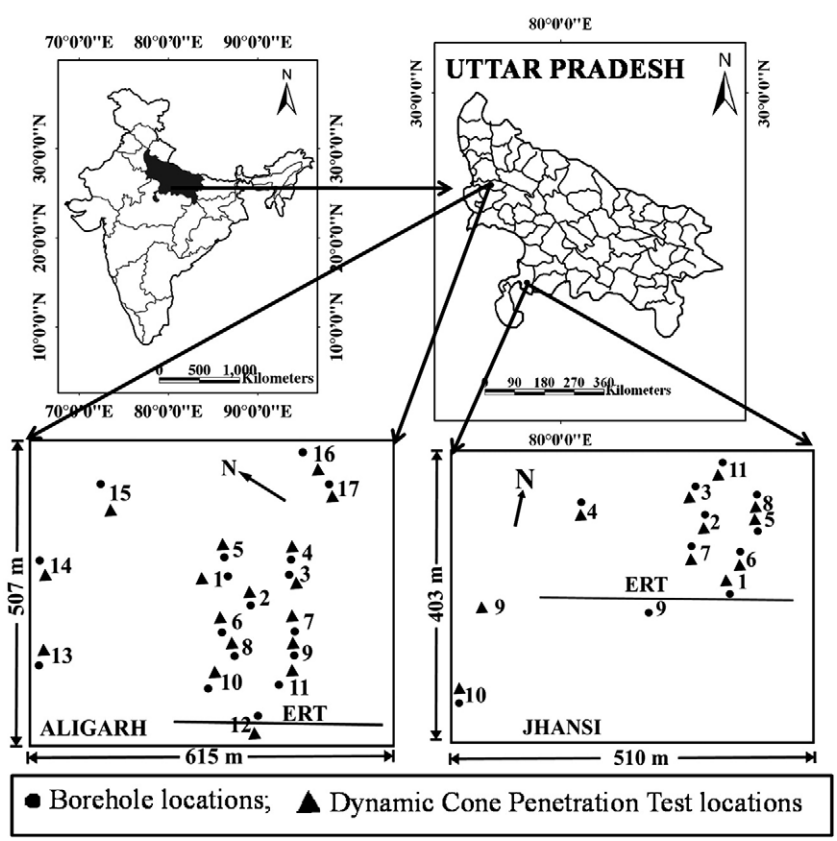

Fig. 1. Location map of the study area, showing the locations of Electrical Resistivity Tomography (ERT), Boreholes (BH) and Dynamic Cone Penetration Test (DCPT) at the investigated sites in Aligarh and Jhansi.

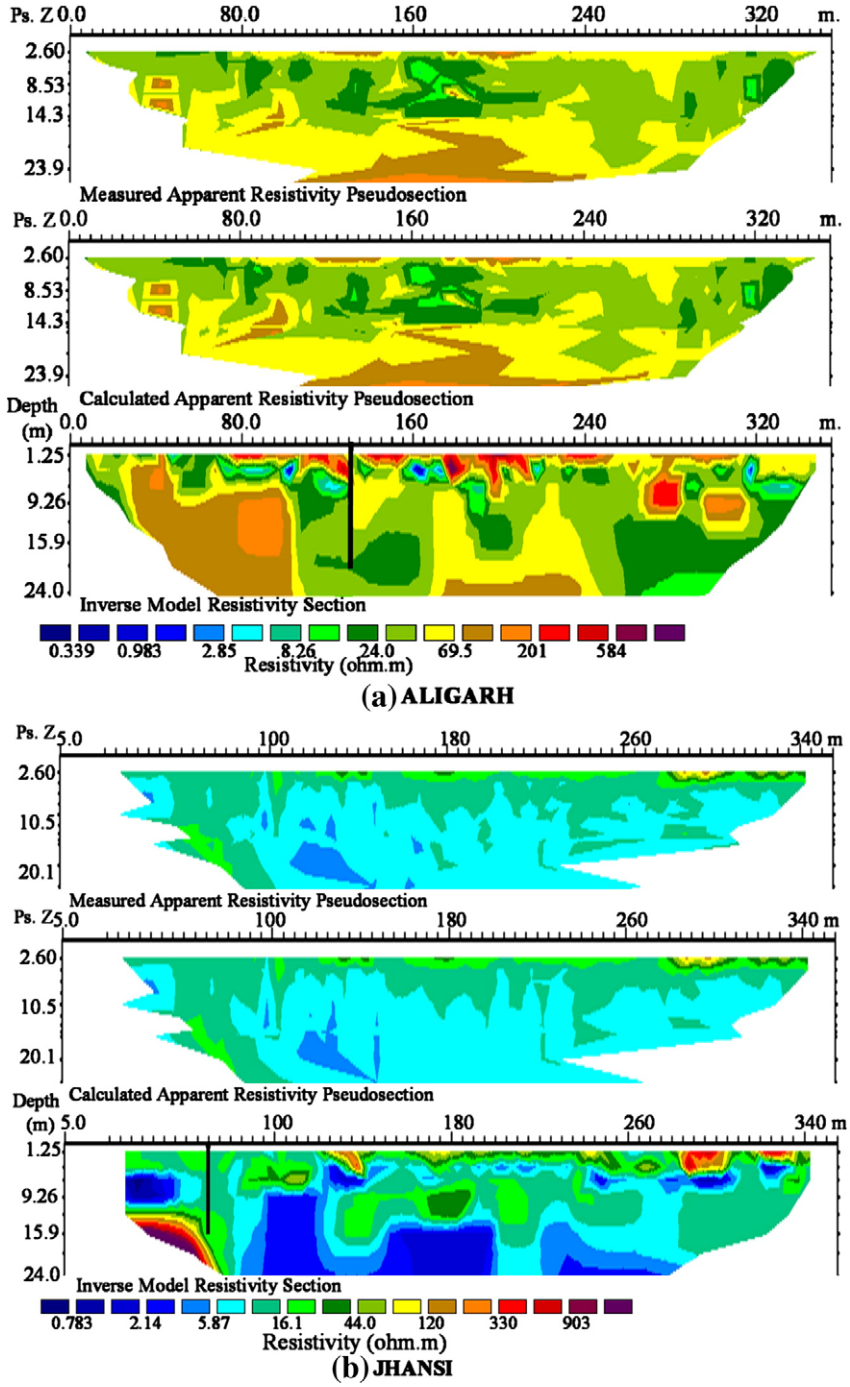

Fig. 2. The raw and modeled resistivity section along the Electrical Resistivity Tomography (ERT) lines (a) Aligarh; (b) Jhansi. (For interpretation of the references to colour in this figure legend,the reader is referred to the web version of this article.)

significant variation of resistivity of soil at different depths along the profile line. The resistivity range at these locations lies between 1 to 1000 Ωm, indicating wide variation in soil matrix, grain size distribution and water saturation.

Resistivity distribution at Aligarh (Fig. 2 (a)) indicates the unsaturated near surface soil represented by high resistivity, almost along the entire profile line. Local high resistivity in the near surface material is due to the presence of boulders exposed on the surface. The thickness of the top layer varies between 2–4 m along the profile line. The decrease in resistivity at a depth below 4 m indicates the presence of saturated soil. Borehole data indicates the presence of static water table at 4 m depth. Clayey formation is represented by a resistivity of less than 10 Ωm. Silty formations are represented by a resistivity range of 10–50 Ωm.

Fig. 2 (b) indicates the similar resistivity-depth model obtained at Jhansi. However, relatively low resistivity at all depths indicates the presence of fine soil material and increase in the percentage of clay in soil matrix. Static water level is recorded at 3.0 m. There are some local high resistivity zones (>200 Ωm) near the surface, indicating localized lateral resistivity inhomogeneities in the near surface material, which are due to the presence of large size dry boulders; such features are observed at this site. The presence of finer materials (silt and clay) in saturation condition, at a depth below 3 m, is indicated by decrease in resistivity. The clay formation is represented by the low resistivity (<10 Ωm) zone.

The ERT results shown in Fig. 2 (a and b) are used for electrical characterization of subsurface soil by generating electrical soil profile at selected locations along the profile line. The electrical soil profile is calibrated with subsurface soil types obtained from the borehole data. Finally, the electrical parameters are correlated with the soil strength as determined from SPT, DCPT and grain size analysis at Aligarh and Jhansi sites.

2.2. Geotechnical investigations

The locations of SPT, DCPT tests and boreholes drilled at Aligarh and Jhansi are shown in Fig. 1. SPT tests were conducted at 17 points to a maximum of 15.5 m depth, following the procedure laid down in IS: 2131-(1981) code. DCPT tests were carried out at 11 points following the procedure mentioned in IS: 4968-(1976) code at Jhansi. In DCPT, 50 mm diameter cone with 60° apex angle was driven into the ground using a 65 kg hammer falling freely from a height of 75 cm. The number of blows (*N*-values) required for the penetration of every 15 cm depth into the ground, was recorded. Soil samples were collected, for grain size analysis, from the boreholes drilled near these locations.

Corrected *N*-values with depth at Aligarh and Jhansi along with the mean blow counts; solid curve, and standard deviation; dotted curve, are shown in Fig. 3 (a and b), respectively. The study area at both sites has alluvial formation, which is generally characterized as layered medium. Any small lateral variation over a local area (≈1 km^2) is taken

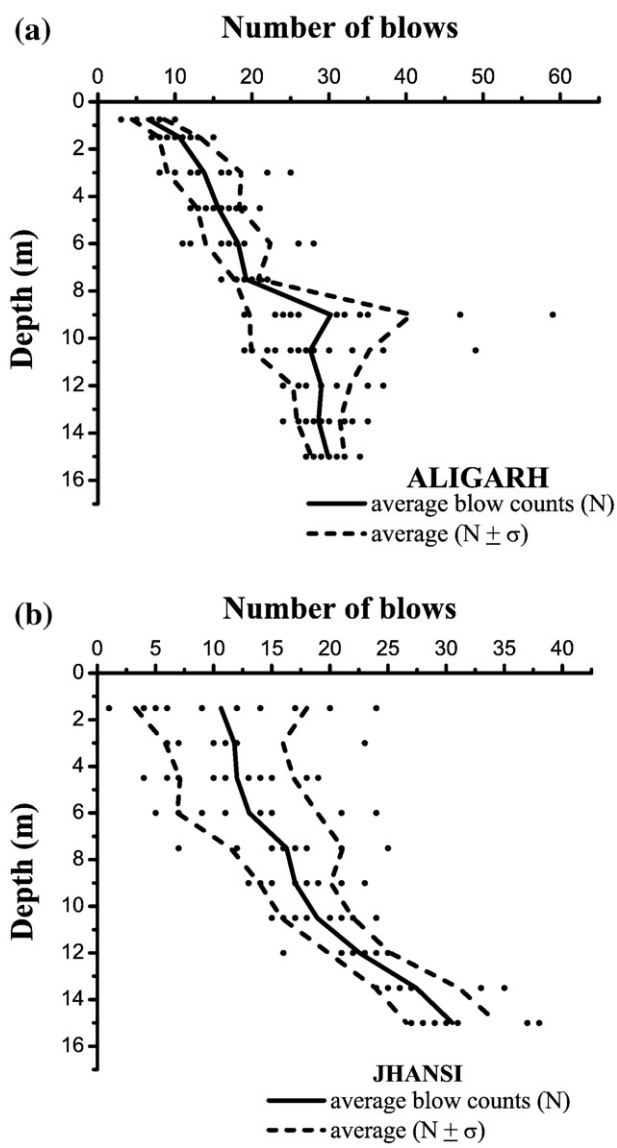

Fig. 3. Variation of number of blow counts (*N*-values) recorded during Standard Penetration Test (SPT) plotted with depth at (a) Aligarh; (b) Jhansi.

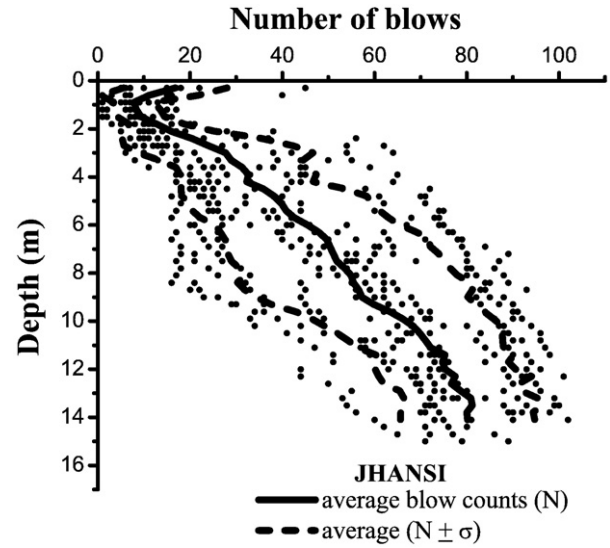

Fig. 4. Variation of number of blow counts (*N*-values) obtained from Dynamic Cone Penetration Test (DCPT) plotted with depth at Jhansi.

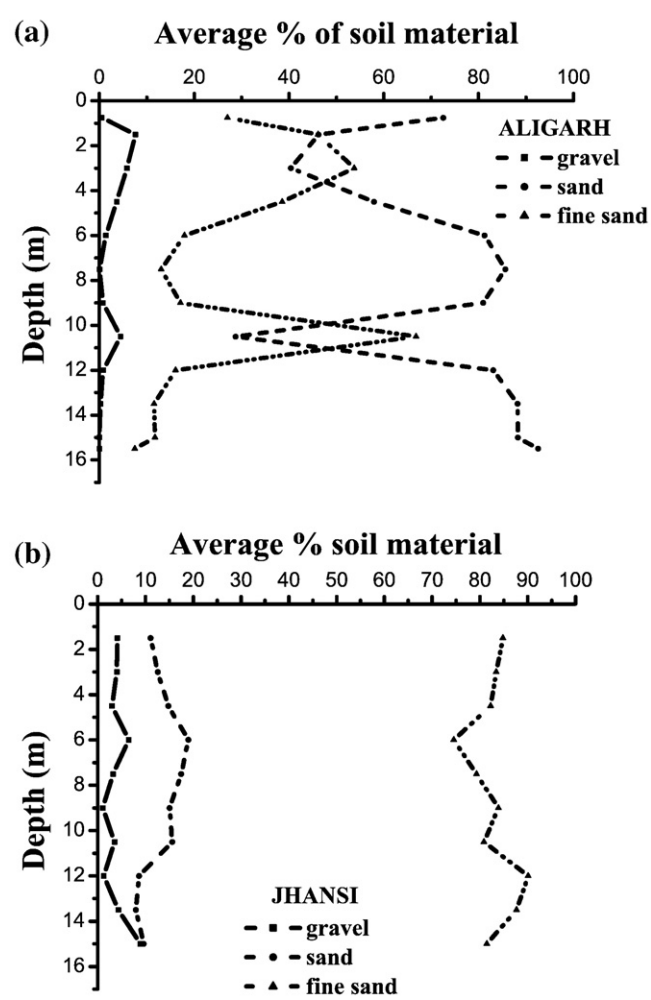

Fig. 5. Particle size distribution in percentage of gravel (>4.75 mm), sand (0.075–4.75 mm) and fine sand (<0.075 mm) obtained from soil sample collected at various depths from (a) Aligarh; (b) Jhansi sites.

care of in averaging of *N*-values. The *N*-values, in general, increase with depth; the rate of increase varies with depth, which depends on the soil strength parameters such as grain size distribution, porosity, degree of saturation, and cementation of soil matrix, etc. The *N*-values obtained from DCPT tests at Jhansi along with their mean; solid curve and standard deviation; dotted curve are shown in Fig. 4.

Laboratory analysis of soil samples collected from these sites was carried out to determine grain size distribution with depth. The average percentage of different particle sizes, gravel (>4.75 mm), sand (0.075 to 4.75 mm), and fine sand (<0.075 mm) plotted with depth at Aligarh and Jhansi sites are shown in Fig. 5 (a and b), respectively. At Aligarh sand is mainly dominating at all depths investigated except between 1.5 to 3.0 m and 9.0 to 12.0 m, where fine sand is dominated (>50%), while at Jhansi fine sand is consistently dominated (>70%), whereas sand is less than 20%. The composition of gravel is very small (<10%) at both sites. The variation of resistivity with the grain size distribution and other parameters are discussed in the following.

In saturated soil, electrical current flow through ions present in the saturating fluid (brine). Soil matrix and grain size distributions offer resistance to the ionic current flow through the fluid present in the pore spaces. If the grain size is very small (<0.075 mm), such as in clay, electrical current will easily flow through the pore fluid making it less

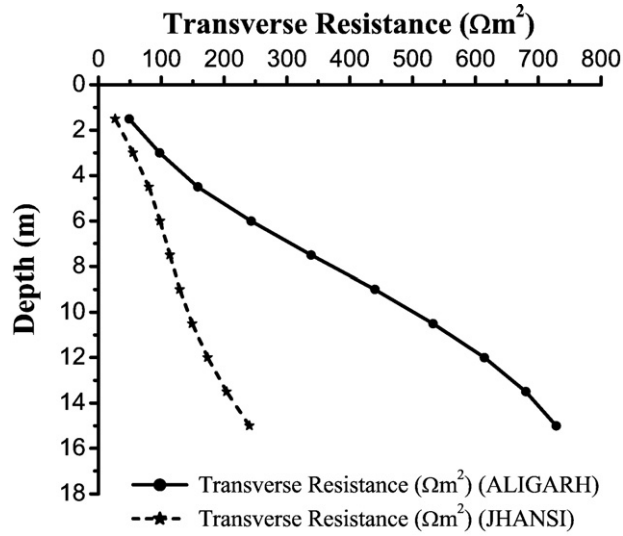

Fig. 7. Variation of transverse resistance with depth at Aligarh and Jhansi sites.

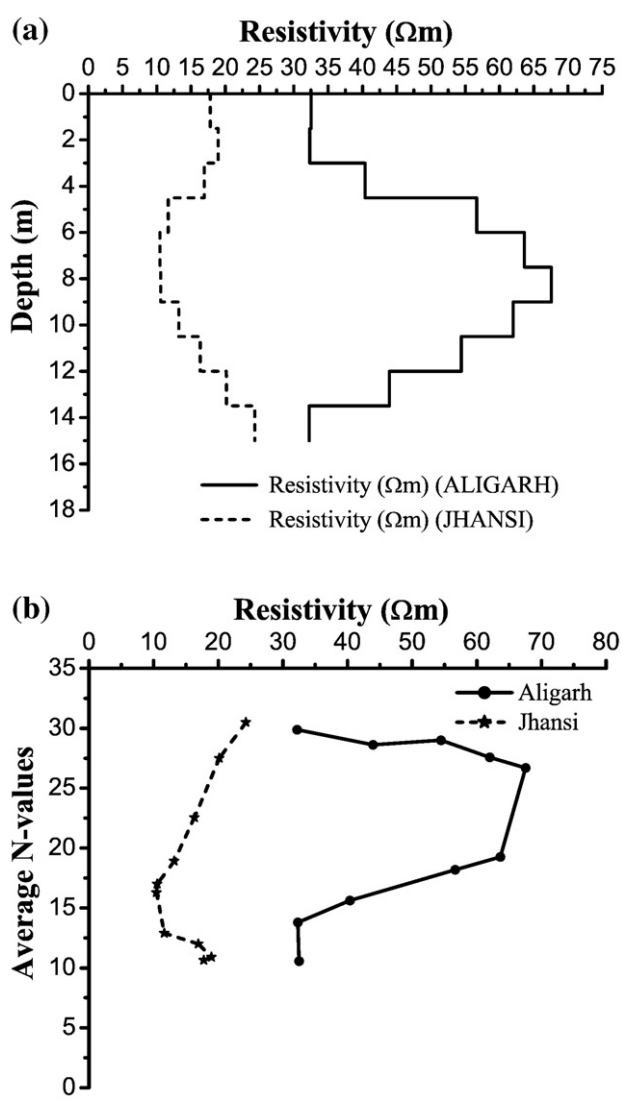

Fig. 6. Variation of resistivity values derived from the interpreted section (a) with depth and (b) with average blow counts.

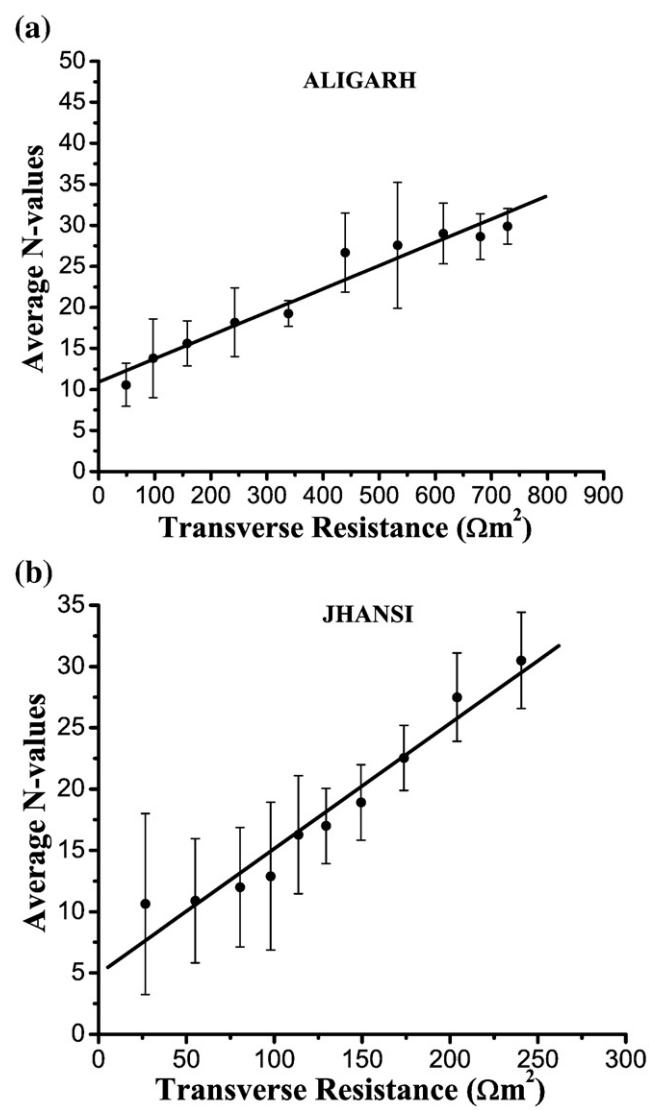

Fig. 8. Linear relationship between number of blow counts (*N*-values) and transverse resistance obtained at (a) Aligarh; (b) Jhansi.

resistive. However, as the grain size increases, it offers more resistance to the ionic current flow. Hence, the bulk resistivity of soil will increase. Archie (1942) has given an empirical relationship between electrical resistivity and porosity of soil. For the constant porosity and saturation, bulk resistivity of soil will increase with increase in grain size (Zhdanov and Keller, 1994). Fig. 2 (a and b) also show the relationship between resistivity and grain size distribution at the investigated sites.

3. Geoelectrical correlation with geotechnical data

Variation of resistivity with depth and average *N*-values at the two investigated sites are shown in Fig. 6 (a and b), respectively. No specific relationships between resistivity and *N*-value are observed in Fig. 6 (b). Similar results were also reported by Braga et al. (1999), Giao et al. (2003).

Further, we have used transverse resistance for correlation with the *N*-values. The transverse resistance (*T*) for m-layer section has been calculated as,

$$T = \sum_{i=1}^{m} \rho_i h_i$$

where ρ_i and h_i is the resistivity and thickness of ith layer respectively. As both sites are located in alluvial area in which no major horizontal discontinuity is expected. Therefore, horizontal average of resistivity over a small profile line (<1 km) is used.

Resistivity values are derived from resistivity depth sections (Figs. 2 and 3) at the depths for which *N*-values were recorded. Fig. 7 shows variation of transverse resistance with depth at the investigated sites.

Fig. 8 (a and b) show linear relations between the transverse resistance and average *N*-values. The coefficients in the linear relations are sensitive to the clay content and lithology at the investigated sites. The linear relationship obtained at Aligarh and Jhansi is given by the following equations respectively.

$$y = 0.028x + 10.909 \quad (2)$$

$$y = 0.102x + 4.922 \quad (3)$$

where abscissa *x* is the transverse resistance (Ωm^2) and ordinate y is the number of blow counts (*N*-values). The coefficients of correlation (*R*) for Eqs. (2) and (3) are 0.974 and 0.975 respectively.

Eqs. (2) and (3) demonstrate that transverse resistance is linearly related with *N*-values at the investigated sites. The differences in the coefficients of linear fit at the two sites are due to the difference in their clay content. At Aligarh, the percentage of clay content is less in comparison to the other sites at Jhansi. This is indicated by the changes in slopes of the linear fit in Eqs. (2) and (3). Positive correlation between the transverse resistance and *N*-value is the main outcome of the present investigation.

4. Conclusion

Geotechnical investigations have been carried out in two different soil types at Aligarh and Jhansi site, in Uttar Pradesh, India. The SPT, DCPT and grain size analysis data have been integrated with the ERT results. Resistivity values are correlated with the soil matrix and grain size distribution. Linear relationship has been presented between transverse resistance derived from the ERT data and N-values obtained from geotechnical tests at these sites. As these sites represent different soil matrix located in different geological environment, the coefficients of linear fit are different. Therefore, the relationships are site-specific and require an extensive study to establish its validity and limitations, in different geological environment, for its future application. Once such relation is known for a particular location, soil strength can be determined from ERT results. The determination of soil strength using ERT is economic, fast and efficient in comparison to the direct in situ methods used to determine the soil strength for civil engineering purposes and, thus, is very useful in geotechnical investigations.

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