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ORIGINAL ARTICLE

Simple and multiple regression models for relationship between electrical resistivity and various soil properties for soil characterization

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Abstract Precise determination of engineering properties of soil is essential for proper design and successful construction of any structure. The conventional methods for determination of engineering properties are invasive, costly and time-consuming. Electrical resistivity survey is an attractive tool for delineate subsurface properties without soil disturbance. Reliable correlations between electrical resistivity and other soil properties will enable us to characterize the subsurface soil without borehole sampling. This paper presents the correlations of electrical resistivity with various properties of soil. Soil investigations, field electrical resistivity survey and laboratory electrical resistivity measurements were conducted. The results from electrical resistivity tests (field and laboratory) and laboratory tests were analyzed together to understand the interrelation between electrical resistivity and various soil properties. The test results were evaluated using simple and multiple regression analysis. From the data analysis, significant quantitative and qualitative correlations have been obtained between resistivity and moisture content, friction angle and plasticity index. Weaker correlations have been observed for cohesion, unit weight of soil and effective size (D_{10}).

Keywords Correlations · Electrical resistivity · Shear strength · Non-destructive testing

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Introduction

Precise determination of engineering properties of soil is essential for proper design and successful construction of any structure (Cosenza et al. 2006). The conventional method of obtaining these engineering parameters is laboratory investigations performed on soil samples acquired from site/field through borehole sampling. However, borehole sampling is generally time-consuming and expensive. Soil properties are subjected to high spatial and temporal variations. Hence, for accurate assessment of soil properties, high-density sampling will be required but borehole sampling would be a very costly and time-consuming option in such condition (Pozdnyakova 1999, 2001). Geophysical methods (geoelectrical, ground penetrating radar, seismic refraction, etc.) have become increasingly practiced in engineering site characterization as being non-invasive, non-destructive, rapid and cost-effective. Among these methods, geoelectrical survey is a very attractive tool for delineating subsurface properties without soil disturbance (Samouëlian et al. 2003).

An electrical resistivity of soil is the measure of its resistance to the passage of current through it. Solid and liquid play a significant role in soil spontaneous electrical phenomena and in behavior of electrical fields, artificially generated in soil (Ozcep et al. 2009). The electrical current flows in soil by electronic and electrolytic conduction. Some specific soil minerals usually metallic minerals conduct current through electronic conduction. However, conducting minerals rarely exist in sufficient quantities to have considerable effect on the electrical properties of soil. Electrolytic conduction is mainly responsible for the flow of current in soils through the movement of ions in pore fluids.

This research work proposes a non-destructive, quick and low-cost method for the assessment of geotechnical problems, such as bearing capacity and factor of safety in soil slopes based on correlations of soil parameters such as cohesion, internal angle of friction, and unit weight with electrical resistivity values.

Several attempts have been made by many researchers to explore the phenomenon of electrical resistivity in soils and its relationship with other soil properties. Water content and electrical resistivity of soil has been successfully correlated by various researchers (Cosenza et al. 2006; Fukue et al. 1999; Kalinski and Kelly 1993; Ozcep et al. 2009, 2010; Pozdnyakov et al. 2006, 2002; Schwartz et al. 2008; Son et al. 2009; Yoon and Park 2001). The obtained correlation models showed nonlinear relationship between soil moisture and resistivity. The knowledge of electrical resistivity is also used to determine thermal resistivity of soil (Erzin et al. 2010; Sreedeep et al. 2005), hydraulic conductivity of compacted clay liners (Abu-Hassanein et al. 1996; Kalinski and Kelly 1994; McCarter 1984), and chemical weathering index (CWI) (Son et al. 2009).

Few studies have been carried out to correlate electrical resistivity and geotechnical parameters of soil. A 2D electrical resistivity survey with Wenner electrode configuration was conducted by Cosenza et al. (2006) to establish qualitative and quantitative correlations between resistivity and cone penetration resistance CPT values. No clear relationship between cone resistance and resistivity was observed and authors suggested an extensive study to be conducted for more reliable correlations. The relationship of electrical resistivity and standard penetration test SPT *N* value was assessed using 2D electrical resistivity tomography at two different sites in India by Sudha et al. (2009). The obtained correlations indicated a site-specific relationship between electrical resistivity and *N* values. A resistivity survey was performed by Braga et al. (1999) in sandy-clay formation and obtained a weak correlation of SPT and electrical resistivity. A thorough study of geotechnical properties and resistivity of clayey soil was conducted by Giao et al. (2003) and found poor correlation between resistivity and plasticity index, unit weight, and organic content of Pusan clay. Abu-Hassanein et al. (1996) performed a comprehensive study on the effect of molding water content and compactive effort in soil resistivity. They also investigated the relationship between soil resistivity and plasticity index and grain-size distribution. Higher resistivity values were observed at optimum dry compaction and lower values were obtained at wet optimum compaction. A curvilinear relationship was found between plasticity index and electrical resistivity of clay and it is concluded that soils with higher plasticity index generally have lower electrical resistivity values.

An investigation of electrical resistivity of soil–cement admixture, at varying cement-mixing ratio, water content and curing time was carried out by Liu et al. (2008). The results show a good correlation of SPT and compressive strength with electrical resistivity of soil–cement admixture. Combined analysis of electrical resistivity and SPT for the assessment of earth filled dam was carried out by (Oh and Sun 2008) and concluded that electrical resistivity of soil has a good correlation with SPT values. It is also suggested that electrical resistivity survey can be used as preliminary tool to assess any troubled subsurface zone and could be later confirmed by geotechnical investigations.

A thorough investigation into the relationship between electrical resistivity and soil parameters (such as cohesion, friction angle, unit weight etc.) was conducted by Syed et al. (2011) on homogeneous samples of sand, silt and clay at laboratory scale. Moisture content found to have strong relationship with resistivity. Poor correlations are observed between cohesion and friction angle with electrical resistivity for sand and silt samples, whereas clay samples showed a good correlation between shear strength parameters and resistivity. Findings of the work is quite encouraging to conduct more field and laboratory investigations in order to establish more reliable relationships between resistivity and soil properties.

Materials and methods

The research methodology consist of both field and laboratory investigations. The study area is located at University Technology PETRONAS, Perak, Malaysia. Field investigations comprise electrical resistivity survey (VES) and soil boring. Laboratory investigations consist of soil characterization tests and electrical resistivity test.

Vertical electrical sounding (VES)

The vertical electrical sounding or 1D survey was conducted at the locations of boreholes (BH-01 to BH-10), using simple equipments and accessories in acquiring the electrical resistivity value e.g. handheld multimeter, D.C. power source, insulated wires, measuring tapes, stainless steel electrodes. The electrical sounding was conducted using Wenner electrode configuration with electrode spacing ranging from 0.5 to 6 m. The apparent electrical resistivity of soil (ρ_a) is determined by Eq. (1)

$$\rho_a = 2\pi RL \quad (1)$$

The obtained apparent electrical resistivity values that were inverted to true resistivity values using Ipi2win software were used for interpretation. IPI2win is an open-source algorithm freely distributed by Moscow State University (Moscow 2012). The procedure for inversion involves automatic and manual technique. Initially automatic inversion was selected in order to get initial model and later on inversion models were refined or fine-tuned using manual method until least RMS error was obtained.

Soil boring

Soil boring was performed using percussion drilling set CobraTT equipped with 1 m core sampler. Depth of all boreholes (BH-01 to BH-10) was 3 m. Prior to drilling PVC pipe was fixed in core sampler for easy and smooth recovery of soil samples from the core barrel. The obtained samples were brought to the laboratory for soil characterization and electrical resistivity test in laboratory conditions.

Soil investigations

The basic idea behind this research is to estimate various soil properties using resistivity values. Therefore, various soil characterization tests were performed to determine engineering properties of soil. Laboratory tests were performed on the soil samples obtained from boreholes BH-01 to BH-10, such as moisture content, unit weight, direct shear, sieve analysis, hydrometer test, liquid limit, plastic limit etc. as per methods suggested in British standards (BS).

Laboratory resistivity test

Electrical resistivity of soil samples from various depths was measured in order to determine resistivity values in laboratory condition. Two disc electrodes were connected to both ends of cylindrical soil samples and also attached to DC power source and multimeter for current measurement. Potential difference varying from 30, 60, and 90 V were applied and resulting variation in current was recorded. Laboratory temperature during electrical resistivity test was recorded as 24 °C.

The electrical resistivity of soil samples were determined by Eqs. 2 and 3. Where V is voltage in volts, I is current in amperes, R is the resistance in ohms, A is the cross-sectional area of soil sample in meters, L is the length of soil sample in meters and ρ is the resistivity in ohms.meter

$$R = \frac{V}{I} \tag{2}$$

$$\rho = \left(\frac{A}{L}\right)R. \tag{3}$$

Results and discussion

Soil investigations results

A total of 79 soil samples were obtained from ten (10) boreholes (BH-01 to BH-10) and brought to geotechnical laboratory for various soil tests (e.g. moisture content, unit weight, direct shear, sieve analysis, hydrometer test, plasticity index, laboratory resistivity test). Locations of all 79 soil samples taken from BH-01 to BH-10 are shown in Fig. 1. Moisture content of soil samples ranges from 6.11 to 52.42 %. Grain-size analysis shows that soil samples from BH-01 to BH-06 are classified as “silty-sand” and soil samples obtained from BH-07 to BH-10 as “sandy” soil samples according to British Soil Classification System (BSCS). Based on grain-size distribution analysis, it can be concluded that 43 soil samples are silty-sand and 36 soil samples are course-grained sandy soils.

Direct shear test results indicate that cohesion of silty-sand soil samples ranges from 3.63 to 68.23 kPa and the mean value is 30.86 kPa. The friction angle values for silty-sand samples ranges between 5.36° and 42.51°. The mean friction angle values measure as 18.12°. The cohesion values for sandy soil samples ranges between 0.00 and 17.41 kPa and average cohesion is 5.25 kPa. The friction angle values ranges from 26.10° to 42.50° and average friction angle is 33.27°. Silty-sand soil samples exhibits higher cohesion and lower friction angle values whereas sandy soils show lower cohesion and higher friction angles.

In plasticity index test all samples were found below the A-line in silt zone (as shown in Fig. 2). Sandy soil samples have lower plasticity index ranging from 0 to 4.60 % whereas silty-sand soils have intermediate plasticity index between 1.41 and 26.27 %.

A little spatial variation was observed in the unit weight of all soil samples. For silty-sand, unit weight ranges between 15.99 and 21.87 kN/m^3 and for sandy soils, unit weight varies from 15.4 to 18.34 kN/m^3. The effective size (D_{10}) is a well-known parameter in soil classification and permeability determination. The effective size D_{10} refers to the maximum size of the smallest 10 % of soil samples. Silty-sand generally exhibits smaller D_{10} ranging from 0.014 to 0.064 mm. Sandy soil samples have higher D_{10} values ranging between 0.08 and 0.389 mm.

Field resistivity survey results

The Ipi2win software was used to interpret and invert the apparent resistivity values obtained during VES survey around the boreholes. The apparent resistivity inversion process produced sub-surface resistivity models for all the boreholes (BH-01 to BH-10). All developed models show multiple layers of different resistivity and thickness.

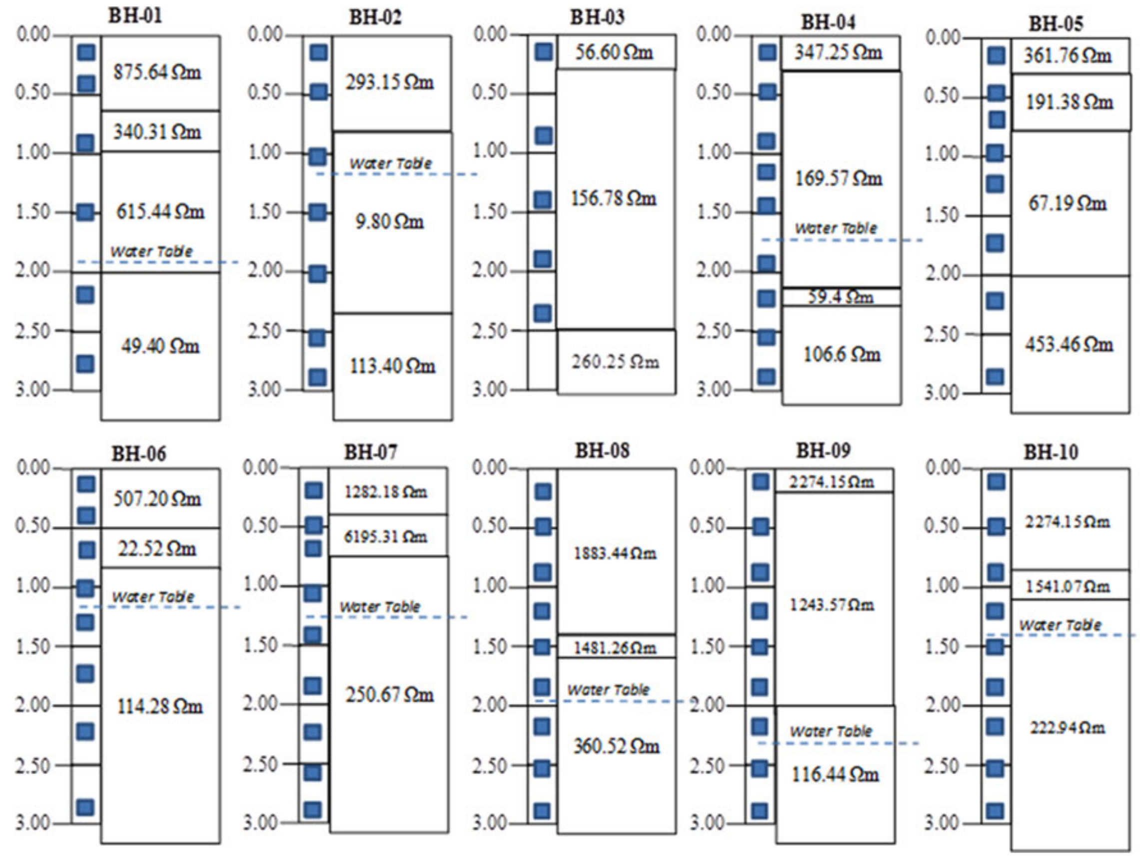


Fig. 1 Locations of soil samples in all borehole columns

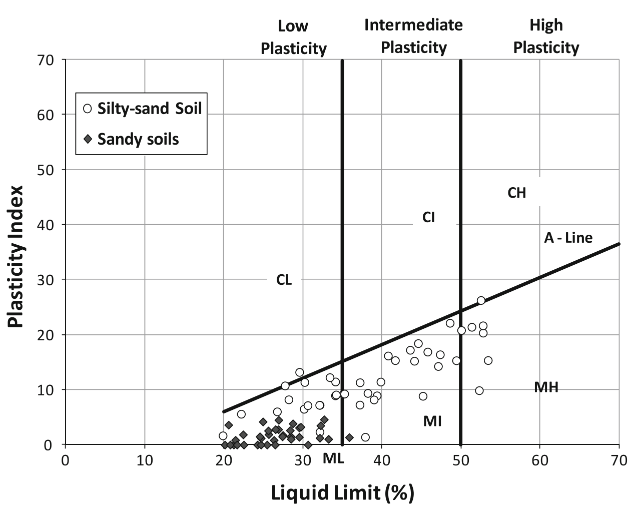


Fig. 2 Plasticity chart of all soil samples

The upper 1–1.5 m in all boreholes is mostly unsaturated indicating higher resistivity values than the bottom portion. The lower portion of all boreholes shows very low resistivity due to the presence of water tables.

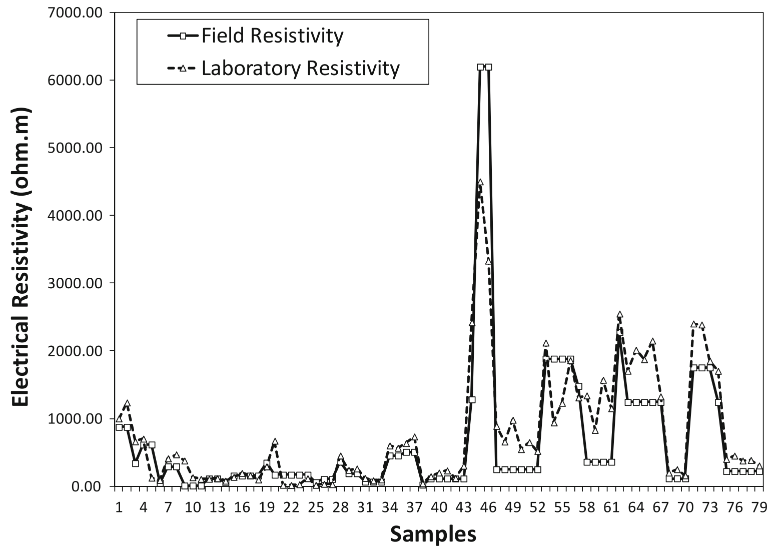
Laboratory electrical resistivity results

The soil samples obtained from all boreholes (BH-01 to BH-10) were subjected to laboratory resistivity measurement in order to determine electrical resistivity of different samples under laboratory conditions. Samples were taken from the different layers of known resistivity values as determined from field resistivity survey, for instance in BH-01, the upper layer has resistivity value 875.64 Ω m and thickness is 0.5 m according to field survey, so that soil samples were taken from upper 0.5 m for laboratory resistivity test. Similarly, all 79 soil samples were taken from different depths in all boreholes.

Comparison of resistivity results

Figure 3 shows variation of electrical resistivity values at different depths obtained by field and laboratory techniques. In general, resistivity values obtained in laboratory are higher than those measured in field due to various reasons such as change in saturation conditions, temperature difference and overburden pressure. The maximum percentage difference in resistivity values obtained at field

Fig. 3 Comparison of resistivity values obtained at field and laboratory



and laboratory is 97 % and minimum variation is 1.22 %. Higher variation in lab and field resistivities is observed for those samples which were obtained from below water table. In case of water table, the field resistivity values are quite lower indicating the water saturated soil. Whereas the laboratory resistivity value of the same soil sample is higher than field resistivity. This high variation is probably due to the change in saturation condition of the soil samples. A good linear trend with $R^2 = 0.76$ was also found between the electrical resistivity values obtained in field and laboratory condition (as shown in Fig. 4).

From the relationship of laboratory and field electrical resistivity values, following linear equation is developed;

$$\rho_{\mathrm{Lab}} = 0.710\rho_{\mathrm{Field}} + 313.2 \quad (4)$$

In Eq. (4), ρ_{Lab} is the resistivity value obtained in laboratory and ρ_{Field} is resistivity value obtained in field.

Simple regression analysis of geotechnical and resistivity data

The results from electrical resistivity tests (field and laboratory) and soil characterization tests were analyzed to understand the relationship between electrical resistivity and various soil properties such as friction angle, cohesion, plasticity index, unit weight, effective size (D_{10}) and moisture content of soil. The correlations between electrical resistivity and various properties of soil samples were evaluated using least-squares regression method. Linear, logarithmic, polynomial, exponential and power curve fitting approximations were applied and the best approximation equation with highest coefficient of determination (R^2) was selected.

Relationship between moisture content and resistivity values demonstrates non-linear correlation. A good power correlation was observed for all soil samples with determination co-efficient $R^2 = 0.56$ (as shown in Fig. 5). Relationship of resistivity with moisture was also determined for each soil type individually. In silty-sand soils, obtained determination coefficient is $R^2 = 0.25$ which is not as strong as it was observed in sandy soils ($R^2 = 0.51$). Electrical resistivity decreases with increasing moisture content in soils as reported in various previous studies (Cosenza et al. 2006; Fukue et al. 1999; Syed et al. 2011; Giao et al. 2003; McCarter 1984; Ozcep et al. 2009, 2010; Pozdnyakov et al. 2006, 1999). Higher moisture content facilitates conduction of electrical current through movement of ions in pore water. Figure 6 compares the moisture–resistivity relationship obtained by the current research and established relationships reported in published literatures (Cosenza et al. 2006; Fukue et al. 1999; Ozcep et al. 2009; Syed et al. 2011).

Unit weight has a very poor relationship with resistivity. Figure 7 indicates a poor polynomial correlation between

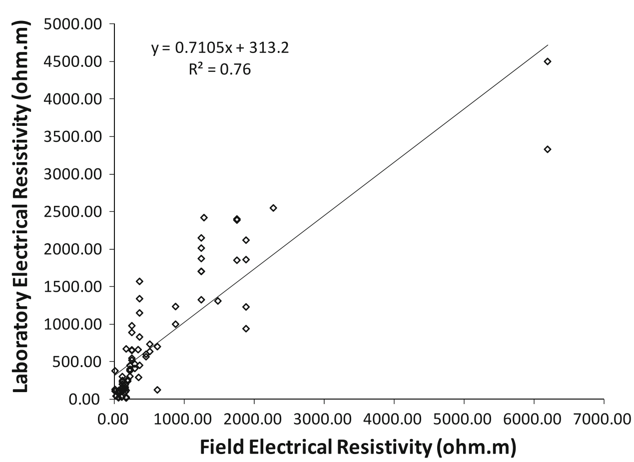


Fig. 4 Correlation between field and laboratory resistivity values

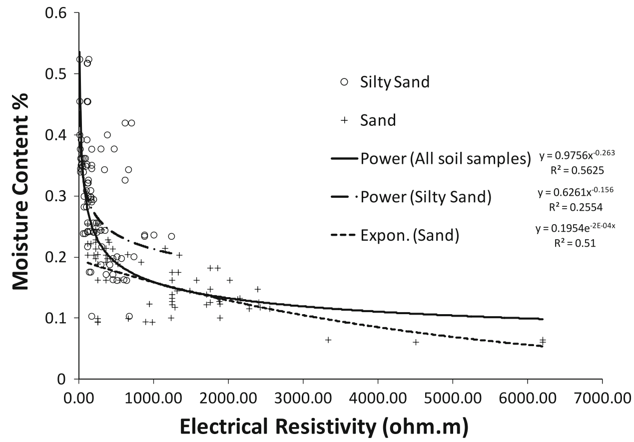


Fig. 5 Correlations of moisture content and electrical resistivity of soil

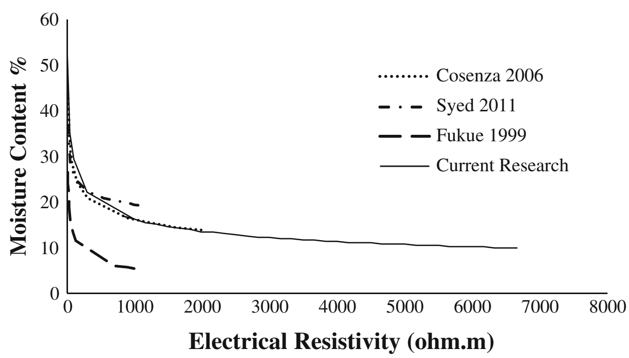


Fig. 6 Comparison of moisture-resistivity model obtained by current research with various published relationships

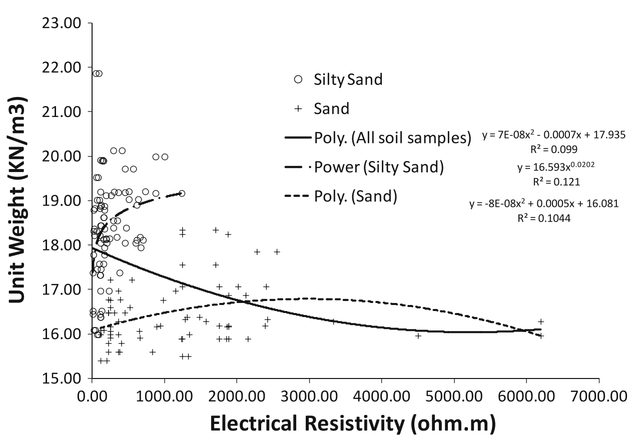


Fig. 7 Correlations of unit weight and electrical resistivity of soil

electrical resistivity and unit weight of soil with determination coefficient $R^2 = 0.10$ for all soil samples. Similarly determination coefficients for silty-sand soils and sandy soils are found to be $R^2 = 0.12$ and $R^2 = 0.10$. It can be concluded that unit weight of soil has no definite relationship with resistivity. Weaker correlations might be due

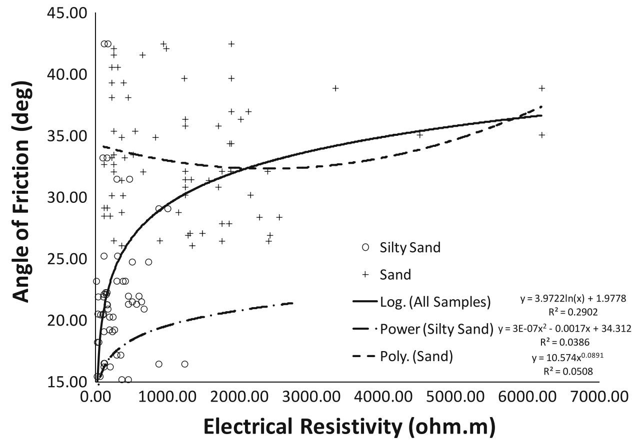


Fig. 8 Correlations of friction angle and electrical resistivity of soil

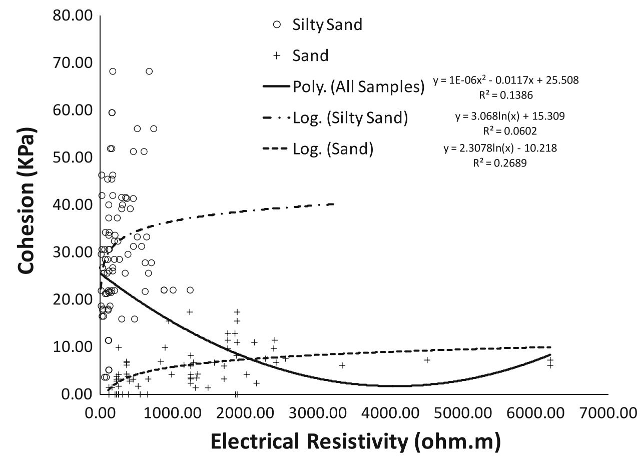


Fig. 9 Correlations of cohesion and electrical resistivity of soil

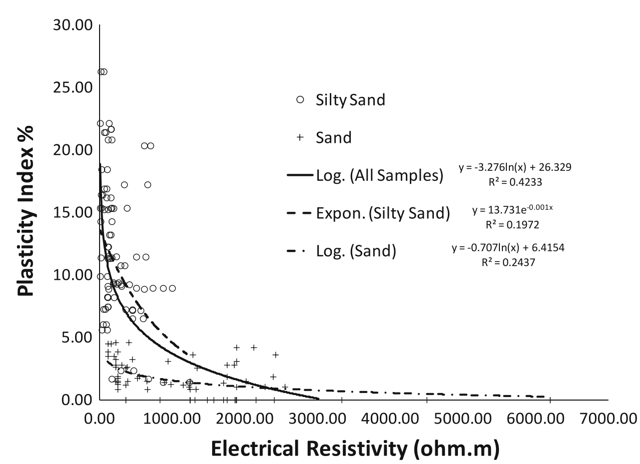


Fig. 10 Correlations of plasticity index and electrical resistivity of soil

to the fact that the unit weight of soil depends more on solid constituents than liquid portion of the soil whereas resistivity is largely affected by moisture content.

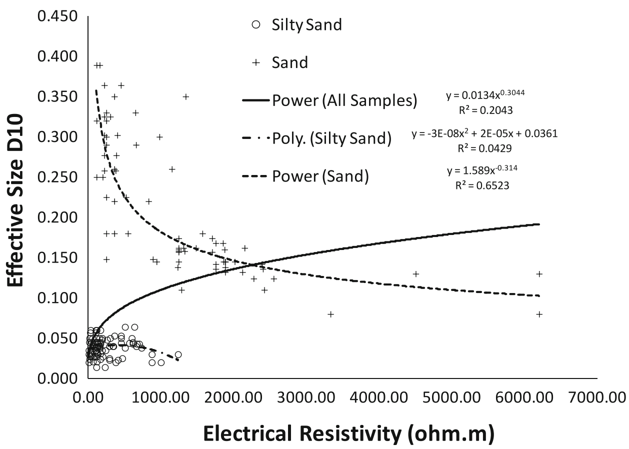


Fig. 11 Correlations of effective size (D_{10}) and electrical resistivity of soil

The relationship between friction angle and resistivity indicates increasing logarithmic trend with $R^2 = 0.29$ for all soil samples (as shown in Fig. 8). It is found that silty-sand soils also have increasing relationship of resistivity and friction angle. The relation between friction angle and resistivity is not well defined in sandy soil. Cohesion has weak relationship with resistivity for all types of soil. Figure 9 shows that the cohesion in silty-sand and sandy soil increases with resistivity.

The obtained behaviors of cohesion and friction angle with resistivity are quite understandable as it is established from literatures (Spoor and Godwin 1979) that shear strength parameters of soil decreases with increasing moisture content thus decreasing the electrical resistivity.

Results indicate a good correlation between plasticity index and resistivity with determination coefficients $R^2 = 0.42$, $R^2 = 0.19$ and $R^2 = 0.24$ for all soil samples, silty-sand soils, and sandy soils, respectively (shown in Fig. 10). Abu-Hassanein et al. (1996) also found similar relationship between plasticity index and resistivity and concluded that soils with higher plasticity index, a greater percentage of fines or clay, or a smaller coarse fraction generally have lower electrical resistivity.

The effective size (D_{10}) is the maximum diameter of soil particles corresponding to 10 % passing on a grain-size distribution curve. Correlations between effective size and resistivity for all type of soils and silty-sand soils show that resistivity will increase as the effective size increases, whereas sandy soil shows a very different relationship indicating that resistivity increases with decreasing effective size (as shown in Fig. 11). The difference in particle size may be the reason for different behaviors in silty-sand and sandy soil. In silty-sand, fine particles tend to reduce the permeability and affect the transmission of fluid thus resulting in increase of resistivity in silty-sand soil. Sandy soils have larger grain size that facilitates the transmission of ion in pore fluid which in turn decreases the electrical resistivity.

Table 1 summarizes the results from simple regression analysis. From Table 1, it can be concluded that resistivity

Table 1 Summary of simple regression analysis results for all types of soils

Soil properties	Sample description	Equations	Determination coefficient (R^2)
Moisture content (%)	All soil samples	$0.9756\rho^{-0.263}$	0.5625
	Silty-sand samples	$0.6261\rho^{-0.156}$	0.2554
	Sandy samples	$0.1954e^{-2E-04\rho}$	0.51
Unit weight (kN/m^3)	All soil samples	$7E-08\rho^2 - 0.0007\rho + 17.935$	0.099
	Silty-sand samples	$16.593\rho^{0.0202}$	0.121
	Sandy samples	$-8E-08\rho^2 + 0.0005\rho + 16.081$	0.1044
Cohesion (kPa)	All soil samples	$1E-06\rho^2 - 0.0117\rho + 25.508$	0.1386
	Silty-sand samples	$3.068\ \ln(\rho) + 15.309$	0.1199
	Sandy samples	$2.3078\ \ln(\rho) - 10.218$	0.2787
Friction angle (°)	All soil samples	$3.9722\ \ln(\rho) + 1.9778$	0.2902
	Silty-sand samples	$3E-07\rho^2 - 0.0017\rho + 34.312$	0.0508
	Sandy samples	$10.574\rho^{0.0891}$	0.0386
Plasticity index (%)	All soil samples	$-3.276\ \ln(\rho) + 26.329$	0.4233
	Silty-sand samples	$13.731e^{-0.001\rho}$	0.1532
	Sandy samples	$-0.707\ \ln(\rho) + 6.4154$	0.2437
Effective size D_{10} (mm)	All soil samples	$0.0134\rho^{0.3044}$	0.2043
	Silty-sand samples	$1.589\rho^{-0.314}$	0.0429
	Sandy samples	$-3E-08\rho^2 + 2E-05\rho + 0.0361$	0.6523

ρ = Electrical resistivity in Ω m

survey method could be a good tool for estimation of moisture content and plasticity index for all type of soils. Cohesion for sandy soil samples is also predictable with moderate accuracy. Friction angle can also be estimated with reduced confidence. Effective size (D_{10}) in sandy soils also has good sensitivity toward electrical resistivity.

Multiple linear regression analysis

Multiple linear regression analysis was carried out using SPSS v.17 in the expectation of obtaining more significant relations for cohesion and friction angle than those of the simple regression. The amount of moisture content affects shear strength parameters as well as resistivity of the soil. For this reason, resistivity and moisture together were included in models for prediction of shear strength parameters. The derived models for the estimation of cohesion and friction angle are as following:

Cohesion:

$$C(\text{kPa}) = 18.986 - 0.005\rho + 14.625\text{wt}\% \quad (5)$$

Friction angle:

$$\phi(^\circ) = 39.187 + 0.001\rho - 61.336\text{wt}\% \quad (6)$$

The determination coefficient of multiple regression model for cohesion is $R^2 = 0.11$ which is less than simple regression model ($R^2 = 0.13$) whereas multiple regression model ($R^2 = 0.45$) for friction angle is higher than that of simple regression ($R^2 = 0.29$).

Conclusion

Electrical resistivity measurement is a non-destructive method and could be applied for quick estimation of soil properties. The obtained correlations between electrical resistivity and various soil properties show a greater possibility to use electrical resistivity survey as an effective in situ assessment tool for predicting some soil properties. From the above results it can be concluded that moisture content, plasticity index and friction angle of soil could be efficiently estimated.

A high spatial distribution was observed in unit weight and resistivity relationship. The relationship of resistivity with cohesion and effective size (D_{10}) of soil mainly depends on soil type, so no generalized equation could be proposed rather different equations were obtained for each soil type.

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