Malaysian Journal of Soil Science Year 2024 Vol. 28, 12-25

Assessing Soil Bulk Density, Plasticity Index, Porosity, and Degree of Saturation through Electrical Resistivity using Correlation Analysis

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ABSTRACT

The factor of safety for soil slopes is a crucial aspect of slope investigations, necessitating a thorough understanding of subsurface soil properties. Traditionally, borehole sampling has been employed for accurate assessment, despite its drawbacks of being costly and time-intensive. However, the emergence of electrical resistivity as a non-invasive technique presents a promising alternative. This method allows for efficient evaluation of subsurface soil properties, requiring minimal time and effort. The study aims to correlate soil properties such as bulk density, plasticity index, porosity, and degree of saturation with the electrical resistivity technique and present possible outcomes. The laboratory-scale Wenner probes method was used for the determination of electrical resistivity. The correlations obtained were analyzed using the correlation analysis method. The correlation between electrical resistivity and plasticity index showed an increased regression value of 0.33 for silty sand samples. For the relationship between resistivity and bulk density, the regression value was 0.32 for clay and silty sand soil samples combined. The correlation between electrical resistivity and porosity for all soil samples and silty sand soil showed R^2 values of 0.20 and 0.36 respectively. However, no relationship was found for clay soil samples while a weak relationship was found for the correlation between degree of saturation and resistivity. The correlations identified suggest that the electrical resistivity method is viable for assessing soil properties, although further comprehensive studies are needed to investigate weak relationships. The outcomes of the study may help bridge the gap in identifying geotechnical and geophysical data.

Keywords: **Geophysical technique, soil properties, correlation model, non-invasive method, borehole sampling**

INTRODUCTION

A critical element of soil science is the investigation of slopes, to identify the factor of safety (FOS) of a particular stretch of slope (Olabode & San, 2023). This is determined by geotechnical experts based on the samples obtained from the borehole sampling technique. This technique allows for accurate subsurface soil determination but is a time-consuming and costly option (Bai *et al*., 2013; Meng *et al*., 2022) as it requires continuous checking and estimation of FOS of a certain stretch of slopes (Arora & Ahmed, 2011). FOS assessment requires a rapid and less costly technique to allow geotechnical engineers to calculate and measure soil bearing capacity and related soil parameters (Gue & Wong, 2009). Geophysical investigations are cost-effective and non-invasive and have been widely used to characterize subsurface geological properties of soil (Qazi *et al*., 2016a; Saha *et al*., 2022). The electrical resistivity method is a geophysical technique adapted to identify the differences in electrical properties. This technique operates by transmitting electric current either to the surface or underground, achieved by inserting electrodes through boreholes to measure the resulting

voltage (Wang *et al*., 2010). Resistivity methods are widely utilized across various earth-related disciplines, including mineral and groundwater resource exploration, geological mapping, and geotechnical engineering (Ducut *et al*., 2022). In this study, the electrical resistivity method is utilized as a substitute for borehole sampling to assess soil properties including plasticity index, bulk density, porosity, and degree of saturation.

Several soil properties influence electrical resistivity, with key factors including water content, porosity, grain size distribution, degree of saturation, pore water salinity, temperature, void ratio, pore connectivity, and pore fluid chemistry (Kibria & Hossain, 2012)(Soares Gerscovich & Vipulanandan, 2023). Various researchers have studied the relationship between electrical resistivity and soil physical properties (Alipio & Visacro, 2014; Rashid *et al*., 2018; Southey *et al*., 2015). (Memon, Osman, *et al*., 2016) proposed a conceptual model to assess the shear strength properties of laterite soil using electrical resistivity technique. Water in the soils greatly impacts the resistivity (Cosenza *et al*., 2006; Friedman, 2005; Qazi *et al*., 2016b; Schwartz *et al*., 2008). (Aranda *et al*., 2021) evaluated the moisture content in a landfill by using electrical resistivity. (Razali & bin Syed Osman, 2011) established a correlation between resistivity and water content using a non-linear approach, demonstrating a robust correlation model. (Memon *et al*., 2017) studied correlations between electrical resistivity and water content for compacted laterite soil. These studies found that electrical resistivity increases with a decrease in the moisture content of soil (Ban *et al*., 2022; Fukue *et al*., 1999; García *et al*., 2012; Ozcep *et al*., 2009, 2010; Pozdnyakov *et al*., 2006; Razali & bin Syed Osman, 2011; Siddiqui, 2012). It is the movement of the ions in pore water that allows the conduction of current through it. (Memon, Azahar, *et al*., 2016) carried out research on correlating laboratory electrical resistivity of laterite soil and bulk density and found significant correlations. Very limited research studies have been conducted on correlating electrical resistivity against porosity and degree of saturation. Therefore, a comprehensive study is required to understand the behavior of resistivity based on these properties. The relationships between soil engineering properties and laboratory (1D) electrical resistivity values can be used to build significant correlation models to help bridge the gap in identifying geotechnical and geophysical data.

MATERIALS AND METHODS

Collection of Soil Samples

Soil specimens were collected from forty distinct locations across the states of Perak, Kedah, and Selangor in Malaysia, including Batu Gajah, Ipoh, Kubang Pasu, Sitiawan, and Banting. The soil samples were obtained between 0.3 m and 0.8 m (disturbed soil) depth. The collection process was followed by manual digging using a harrow. Three plastic bags were prepared to obtain the samples; usually, the amount of soil collected was about 30 kg (including raw materials). The soil was then brought to the laboratory and dried in the oven for 24 hours. The subsequent phase involved sieving the soil in a 2 mm sieve until 15kg of soil was obtained. The samples collected from the site were tested at the Geotechnical Laboratory of Universiti Teknologi PETRONAS, Malaysia. Electrical resistivity and soil characterization tests (plasticity index, bulk density, porosity, and degree of saturation) were performed on the soil samples. The data obtained from the experiments was analyzed using regression analysis. The comprehensive methodology flowchart for the current study is depicted in Figure 1.

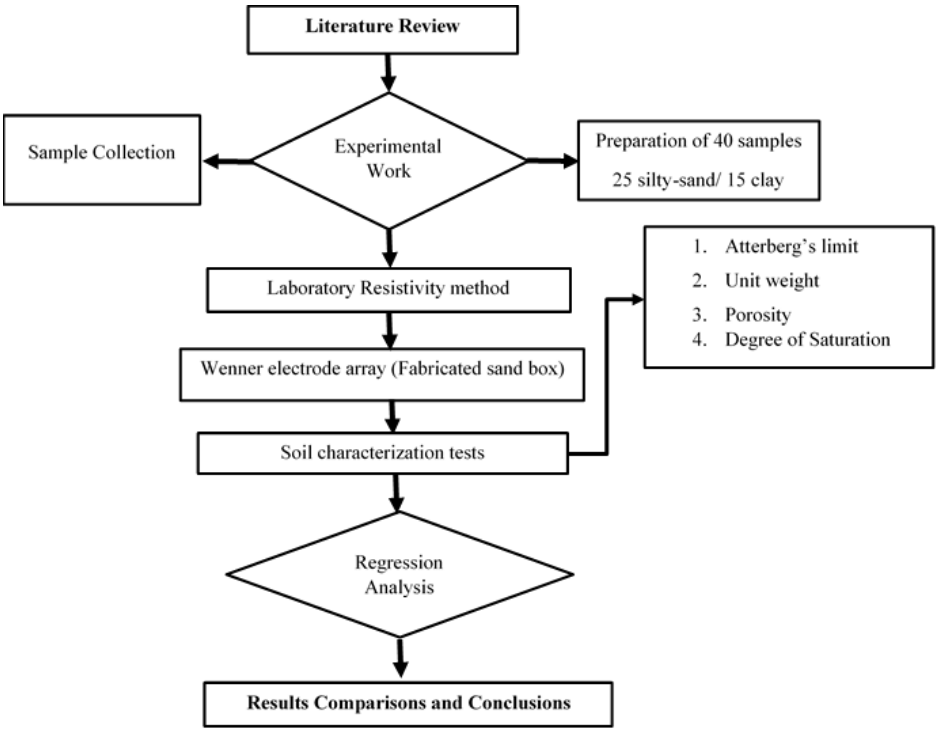

Figure 1. Complete experimental scheme for this research project

Atterberg's Limits Tests

Tests that were run on Atterberg's limits included both liquid and plastic limits tests and were according to techniques recommended in BS standard 1377: Part 2: 1990. For plastic limit tests, 10 gm of soil was formed into ellipsoidal soil masses by adding water. Soil masses were moved onto a glass plate to form a string of 3 mm. If threads appeared broken or cracked, then they were subjected to a moisture test. Figure 2a illustrates a standard procedure for determining the plastic limit of soil.

The fall cone penetrometer test was executed to calculate the liquid limit of soil. According to the prescribed test, the liquid limit of the soil is the moisture content at 80 gm along with a 30° steel cone entering precisely at 20 mm into the mass of remolded soil for 5 sec. This moisture level is considered the critical moisture content of a given soil sample. As it is extremely difficult to obtain a precise 20 mm infiltration, 3 or 4 trials are performed. Initially, a small amount of water is added to the soil sample resulting in cone penetration at around 15-16 mm. Similarly, in each trial, the amount of water added to the soil sample is increased and the resulting penetration increases as the soil gets softer. The graph illustrates the relationship between soil moisture content (%) and cone infiltration (mm), with a particular focus on the liquid limit, represented by the 20 mm infiltration point. Figure 2b shows the exploratory setup for the liquid limit test utilizing the fall cone strategy.

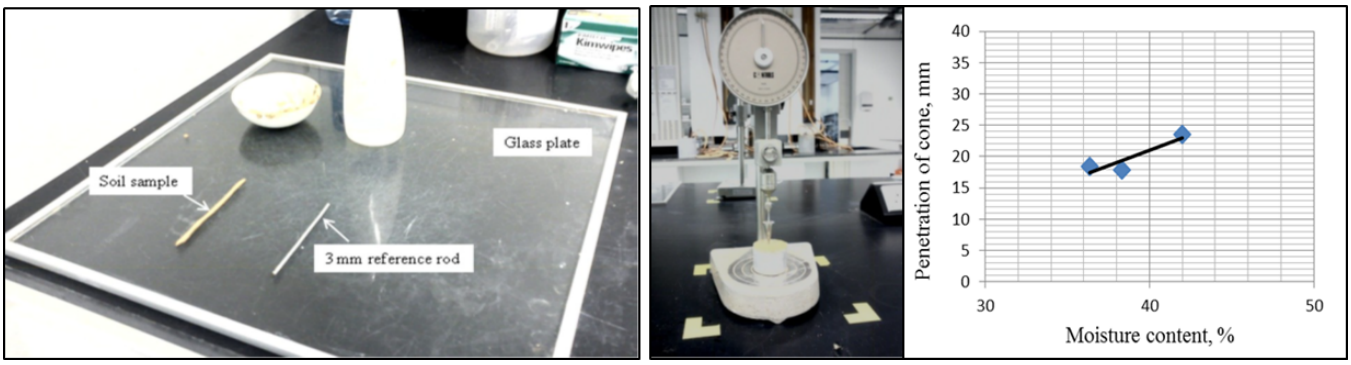

Figure 2. (a) Arrangement of Plastic Limit test; (b) Cone penetrometer and example showing the calculation of liquid limit

Determination of Bulk Density

The bulk density of soil tests was determined according to the method proposed in BS 1377: Part 2: 1990 using Equation (1):

$$\gamma_d = \frac{100 \times \gamma_b}{100+w} \quad (1)$$

where

γ_d = dry unit weight of soil

γ_b = bulk unit weight (m/V)

$W\%$ = moisture content in soil

Determination of Porosity

Porosity or pore space is the amount of air space or void space between soil particles. The porosity of soil or geologic materials is the ratio of the volume of pore space in a unit of material to the total volume of material. It is also determined by using the formula in Equation (2) according to BS 1377: Part: 2.

$$Porosity = \frac{e}{1+e} \quad (2)$$

where

e = void ratio

The void ratio can be calculated from Equation (3) as

$$e = \frac{Gs}{\gamma_d} - 1 \quad (3)$$

Determination of Degree of Saturation

Saturation is a condition in which all easily drained voids or pores between soil particles are temporarily or permanently filled with water. The water content and dry unit weight can be combined into a single geotechnical parameter called the degree of saturation. The degree of saturation, (Sr) is defined as the ratio of the volume of water to the volume of voids. It can range between 0% for completely dry soil and 100% for fully saturated soil. The degree of saturation is determined by the formula given below in Equation (4).

$$S = \frac{w\rho s}{e} \quad (4)$$

where

W = moisture content
ρs = specific gravity of soil
e = void ratio

Wenner Probe Method

This method was put forward by Frank Wenner, US Bureau of Standards in 1915. The approach was based on four electrodes with equal spaced distances. The four probes were installed in the ground, two of which were used for injecting the current and the remaining two were utilized to measure the voltage drop. The method of testing using four electrodes has been a practice since 1931 for assessing soil water content and salinity under different atmospheric conditions (Smith, 2013). Moreover, the Wenner electrode method has been used to measure the electrical resistivity or conductivity in the field of geology and soil science. It is important to acknowledge that electronic technologies have revolutionized procedures through new mechanisms that allow us to evaluate things more easily with fewer errors (Pozdnyakova *et al*., 2001). Figure 3a illustrates the typical arrangement of the four-pin Wenner method used in this study.

Electrical Resistivity Setup at Laboratory

Fifteen kg of *in situ* soil was sieved and prepared based on the methodology mentioned in the section on a collection of soil samples for laboratory resistivity survey. The electrical resistivity of the soil was measured by incorporating the Wenner probe method in the fabricated sandbox as shown in Figure 3b. The soil characterization tests performed conformed to the British standards (Standard, 1990).

Correlation Analysis Method (CAM)

The correlation analysis method (CAM) was applied to establish correlations between electrical resistivity and soil properties. The equation of the best-fit line together with the determination of coefficient (R^2) was established. The correlation between electrical resistivity and soil parameters was assessed utilizing the least-square regression technique.

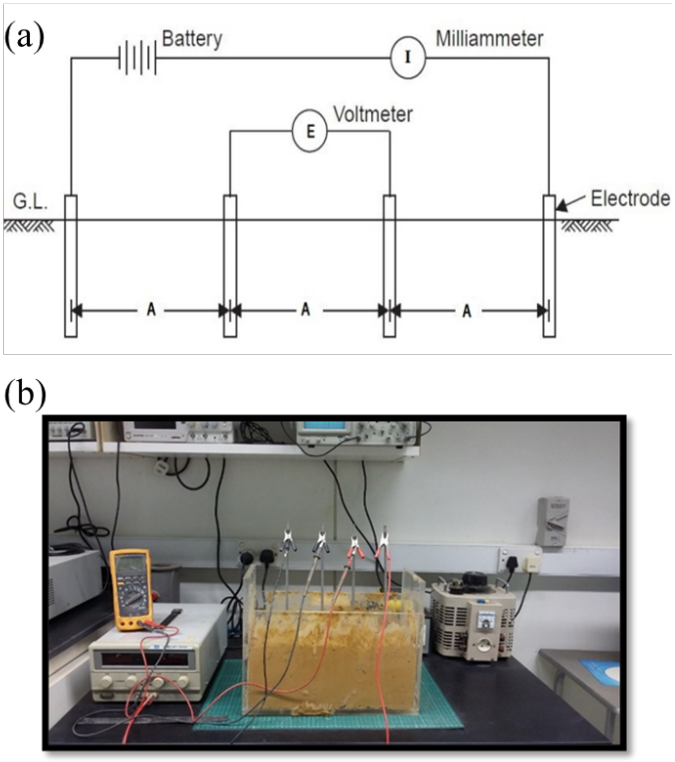

Figure 3. (a) Example of four-pin Wenner electrode method; (b) Laboratory-scale Wenner Array setup in a sandbox

RESULTS AND DISCUSSION

Soil Analyses

A bulk density test was conducted using a steel sampler. Values for various soil samples were found to range from 18.35 kN/m^3 to 20.05 kN/m^3. Figure 4a presents the distribution of bulk density for all soil samples. For the plasticity index test (PI), 25 soil samples fell in the silty-sand type with values ranging from 8.88% to 24.4% while the remaining samples behaved as a clay-soil mixture. Silty-sand soil showed lower plasticity index values compared to the PI of the clay soil samples which ranged from 25.04% to 39.25%. Figure 4b presents the distribution of the plasticity index in all soil samples.

For porosity and degree of saturation, the values varied and ranged from 27.73% to 51.88% and 74.57% to 99.46% respectively, as shown in Figures 4c and 4d.

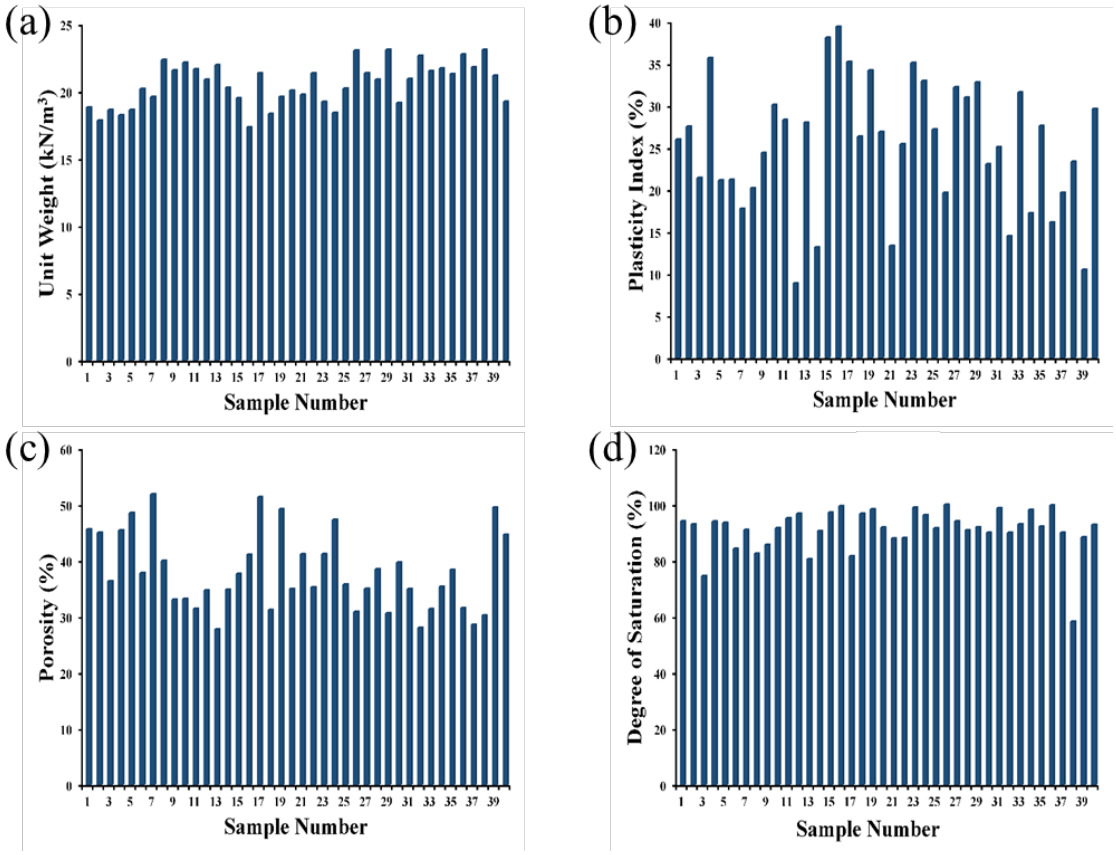

Figure 4. The distribution of bulk density for all soil samples

Correlation of Resistivity with Soil Engineering Properties

The main aim of this research is to establish a correlation between resistivity values acquired under laboratory conditions. Usually, resistivity numbers acquired from the laboratory examination are found to be higher than those estimated in the field due to distinct reasons for changes in saturation conditions, differences in temperature, and overburden pressure. The outcomes attained from electrical resistivity investigation (1D-VES laboratory) and soil characterization were compared to understand the relationship between electrical resistivity and soil parameters, for example, plasticity index, bulk density, porosity, and degree of saturation. Resistivity values obtained from laboratory analysis were independently correlated with various soil properties.

(1) Resistivity Relationship with Plasticity Index

The plasticity index values did not show a good correlation with laboratory resistivity measurements. Most of the obtained samples were silty-sand in nature with values that ranged from 8.88% to 24.45%. The coefficient of regression for all soil specimens (clay and silty-sand soils) was found to be 0.19, 0.075, and 0.309 respectively. In the case of clay soil, the regression value was very low. Polynomial curve fitting was applied to correlate resistivity to plasticity index for silty-sand and clayey mixtures as shown in Figure 5. The equations and regression values derived from the correlation for all three soil types are presented in Table 1.

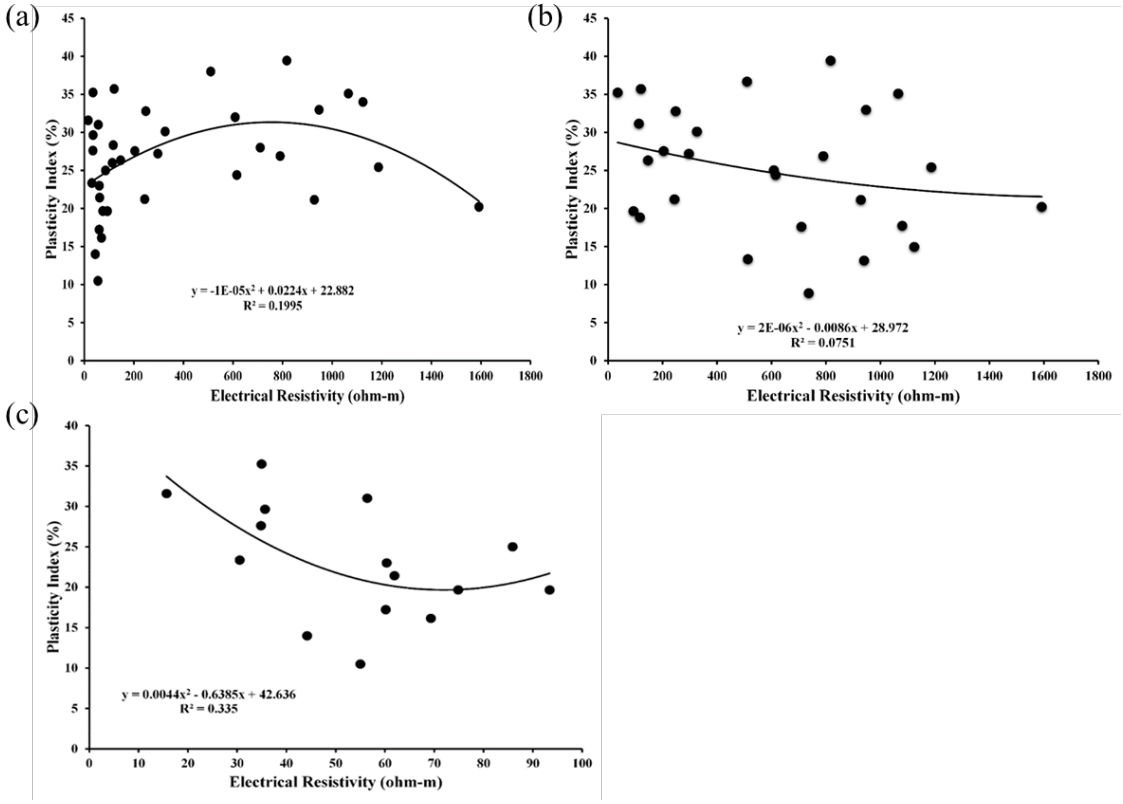

Figure 5. Correlation between electrical resistivity and plasticity index for (a) all soils, (b) clay soil, and (c) silty-sand soil

Table 1. Equations and regression values for plasticity-resistivity correlations

Components	Soil type	Equation	Regression
Plasticity Index	All soils	$PI\% = -1\times10^{-5}\,\rho^2 + 0.0224\rho + 22.882$, (5)	0.19
	Silty-sand soil	$PI\% = 2\times10^{-6}\rho^2 - 0.0086\rho + 28.972$, (6)	0.309
	Clay soil	$PI\% = 0.0044\rho^2 - 0.6385\rho + 42.636$, (7)	0.075

Previous studies reveal a reasonably good relation between plasticity index and resistivity. (Abu-Hassanein *et al*., 1996) demonstrated that soil with a greater amount of finer or clay particles normally has a high plasticity index but lower electrical resistivity. This may be due to grain size distribution which allows the water to flow smoothly, thus increasing electrical conductivity. Their scope of study was confined to a resistivity range of 30Ω to 5Ω with the plasticity index being between 5% and 45%. On the other hand, (Siddiqui, 2012)also obtained a similar trend with the electrical resistivity and plasticity index relationship, hence suggesting that the values of resistivity lie between 120 Ω and 6000 Ω with the plasticity index ranging between 5% and 26%. Figure 6 shows a comparison of the results of the current study with previous studies by (Abu-Hassanein *et al*., 1996) and (Siddiqui, 2012). It could be inferred that the current research does not support the relationship of the resistivity-plasticity index found in the previous studies due to the difference in particle size characterization. Soil consisting of different grain sizes is not a homogeneous material. It is known that clayey soils have lower electrical resistivity values than sandy soils and that saturated sandy soils might indicate lower resistivity values than dry compacted clayey soil.

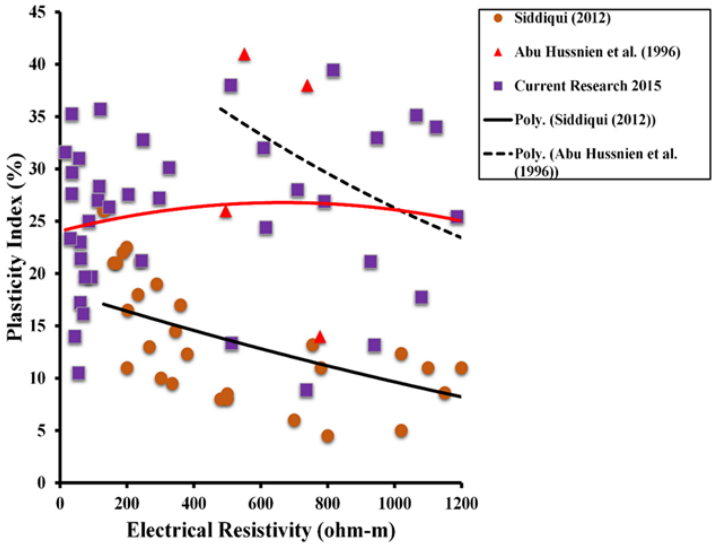

Figure 6. Comparison of plasticity index-resistivity model obtained from current and previous studies (Abu-Hassanein *et al*., 1996; Siddiqui, 2012)

(2) Resistivity Relationship with Bulk density

The bulk density of the soil showed a weak correlation with laboratory electrical resistivity values. Figure 7a indicates a poor polynomial relationship between the selected parameters. The regression coefficient obtained was 0.20 for all soil samples. The poor correlation observed may be attributed to the significant influence of the solid component of soil on bulk density, in contrast to the liquid component. Meanwhile, soil resistivity is primarily influenced by the moisture content within the soil's pore spaces. As illustrated in Figure 7b, there is a better correlation between soil bulk density and moisture content. The combined correlation model between bulk density and resistivity for silty sand and clay soil can be observed in Figure 7c. Table 2 shows the equations and regression values for the bulk-density and resistivity relationship. This study showed improved polynomial correlation for silty-sand soil samples as compared to the clay samples shown in Figure 7c. (Giao *et al*., 2003) and (Razali & bin Syed Osman, 2011) also found a similar relationship between bulk density and electrical resistivity in various clay soil mixtures as shown in Figure 8.

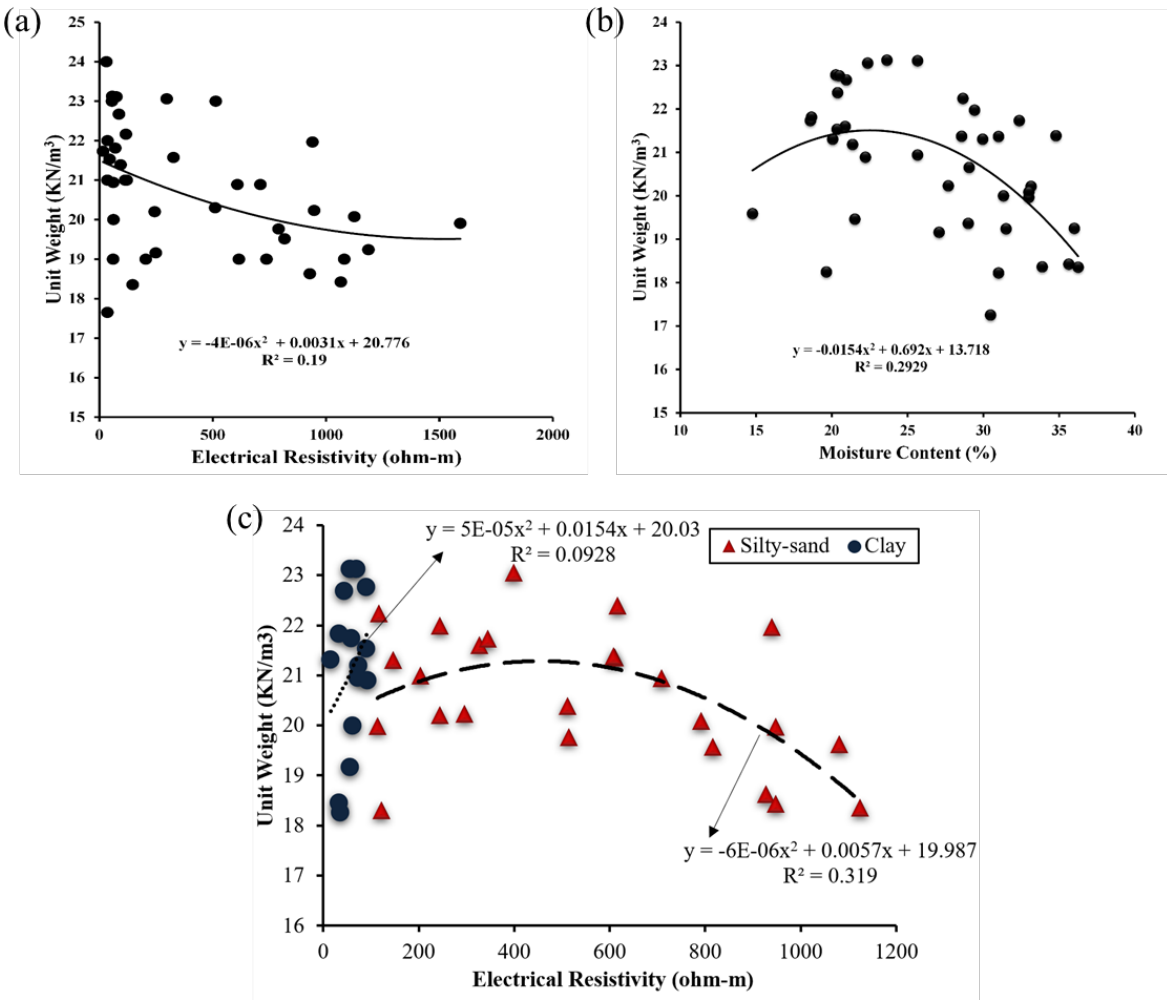

Figure 7. (a) Relationship between bulk density and resistivity for all soil samples; (b) Relationship between bulk density and moisture content for all soil samples; (c) Combined correlation between bulk density and electrical resistivity in both clay and silty-sand soils.

Table 1. Equations and regression values for bulk density-resistivity correlations

Components	Soil type	Equation	Regression
Bulk density	All soils	$Y = -4\times10^{-6}\rho^2 + 0.0031\rho + 20.776$, (8)	0.20
	Silty-sand soil	$Y= -6\times10^{-6}\rho^2 + 0.0057\rho + 19.987$, (9)	0.319
	Clay soil	$Y = 5\times10^{-5}\rho^2 + 0.0154\rho + 20.03$, (10)	0.10

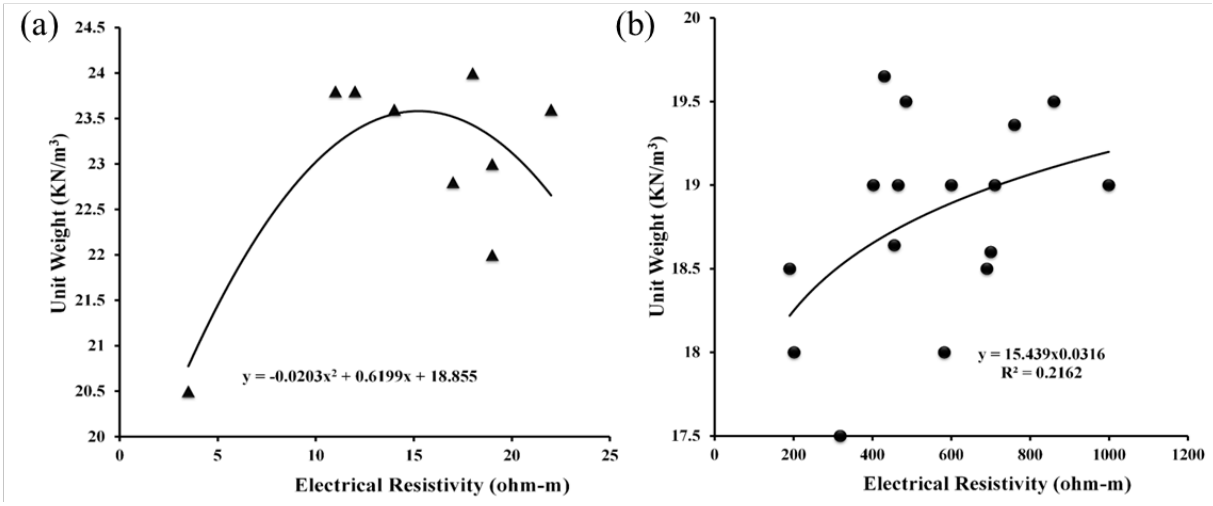

Figure 8. (a) Correlation between bulk density and resistivity as demonstrated in a prior study; (b) Correlation between bulk density and resistivity advocated by(Razali & bin Syed Osman, 2011)

(3) Resistivity Relationship of Porosity with Degree of Saturation

Polynomial curve fittings were applied to obtain the relationship between porosity and degree of saturation against electrical resistivity. In Figure 9a, there is no apparent correlation observed, as porosity decreased at certain points with increasing resistivity, while the degree of saturation exhibited a weak correlation model. The regression coefficient for porosity and degree of saturation was determined to be highly insignificant. Porosity is primarily influenced by particle size distribution, whereas moisture content has a significant impact on the degree of saturation. To circumvent potential challenges associated with extracting soil water content, replaceable cations (Ca/Mg) can serve as intermediaries for pore water properties to align with Archie's Law under site-specific conditions. Furthermore, (Kibria, 2014) showed that rates of pore water properties were directly associated with Cation Exchange Capacity (CEC). Consequently, the impact of soil properties on the electrical conduction of soils can be represented by CEC (Kibria, 2014; Shah & Singh, 2005). An increase in the degree of saturation results in improved particle bridging, thereby enhancing pore connectivity as the presence of dielectric air voids decreases with higher degrees of saturation. Figure 9b depicts the correlation between porosity and resistivity for silty-sand soil, evidenced by a regression coefficient of 0.35. Conversely, the relationship between the degree of saturation and resistivity is characterized by a regression coefficient of 0.16. Figure 9c illustrates the fluctuations in the correlation between electrical resistivity values and porosity, as well as the degree of saturation, for clay soils. The findings reveal a rising trend in porosity, while the degree of saturation demonstrates a decrease with increasing electrical resistivity. The equations derived for the relationship between resistivity, porosity, and degree of saturation are presented in Table 3.

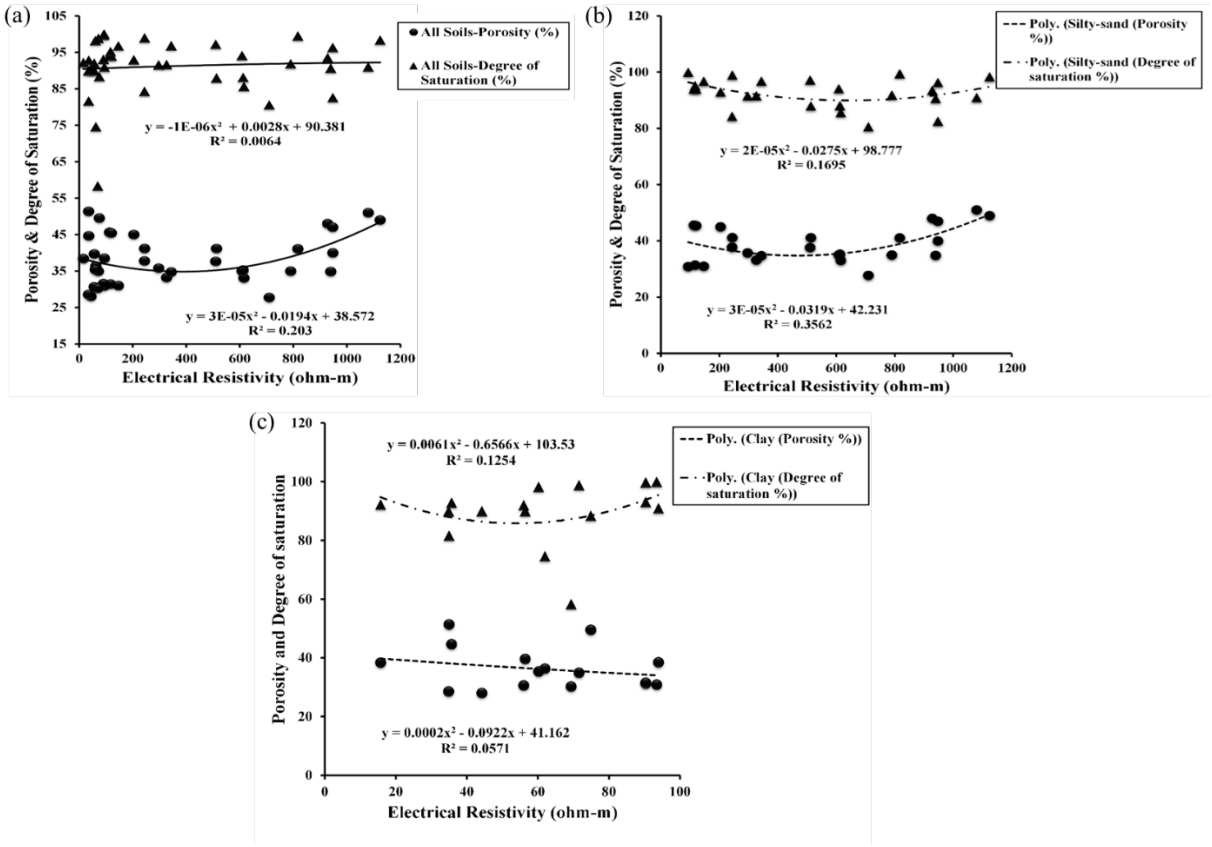

Figure 9. Correlation of porosity and degree of saturation against resistivity for (a) all soil samples, (b) Silty-sand soil samples, and (c) Clay soil samples.

Table 3. Equations and regression values for porosity/degree of saturation-resistivity relationship

Components	Soil type	Equation	Regression
Porosity	All soils	$P = 3E\text{-}05\rho^2 - 0.0194\rho + 38.57$, (11)	0.203
	Silty-sand soil	$P = 3E\text{-}05\rho^2 - 0.0319\rho + 42.231$, (12)	0.356
	Clay soil	$P = 50.392\rho\text{-}0.086$, (9)	0.049
Degree of saturation	All soils	$S = -1E\text{-}06\rho^2 + 0.0028\rho + 90.381$, (13)	0.006
	Silty-sand soil	$S = 2E\text{-}05\rho^2 - 0.0275\rho + 98.777$, (14)	0.169
	Clay soil	$S = 0.0061\rho^2 - 0.6566\rho + 103.53$, (15)	0.125

CONCLUSION

The electrical resistivity method, being non-destructive, serves as a valuable tool in determining soil properties. In this study, soil properties such as plasticity index, bulk density, porosity, and degree of saturation were investigated in the laboratory and correlated with electrical resistivity. The correlation analysis revealed notable findings. Specifically, the correlation between electrical resistivity and plasticity index exhibited an increased regression value of 0.33 for silty sand samples. Similarly, the relationship between resistivity and bulk density yielded a regression value of 0.32 for both clay and silty sand soil samples. However, further experiments are warranted to fully elucidate the relationship between soil bulk density and laboratory electrical resistivity. Moreover, the correlation analysis between electrical resistivity and porosity demonstrated R^2 values of 0.20 for all soil specimens and 0.36 for silty sand soil samples, while no significant relationship was observed for clay soil samples.

Furthermore, the correlation of the degree of saturation with resistivity indicated a poor relationship. These findings underscore the complexity and variability of soil properties and emphasize the need for continued research in this field.

ACKNOWLEDGEMENTS

The authors declare no conflicts of interest. This work was financially supported by the China Scholarship Council (No. 202306370184), and the Fundamental Research Funds for the Central Universities of Central South University (NO. 2021zzts0866).

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