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An Overview of Relationship between Hydro-Thermo-Mechanical Soil Parameters and Electrical Resistivity

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Abstract

With an emphasis on establishing a connection between electrical and sub-surface hydro-geophysical features of soils, a critical evaluation of electrical resistivity technique applications is conducted in the current work. In order to identify diverse subsurface soil characteristics at different stratifications, the electrical resistivity approach is a widely utilized geophysical method that is extensively adopted in various Earth landforms. The assessment of sub-surface hydro-geophysical features of soils, on the other hand, offers information on the hydrogeological and geological properties including the classification of aquifer types, groundwater pollution, and seismic data. The vast majority of the information compiled in this work may help the researchers better understand some basic fundamental issues relating the hydrogeology.

Nomenclature		Nomenclature	
H	Depth (m)	W	Watts
ER	Electrical resistivity (Ω-m)	k	Thermal conductivity (W/m.K)
R^2	Coefficient of determination	LL	Liquid limit
R	Correlation coefficient	PL	Plastic limit
N	Number of blow counts	PI	Plasticity index
Φ	Internal angle of friction (°)	LS	Linear shrinkage
C	Cohesion of soil (in KPa)	γ	Unit weight (Kg/m^3)
q_{bc}	Bearing capacity of soil (in KN/m^2)	G_s	Specific gravity
n	Porosity (%)	T_e	Transmissivity (m^2/day)
e	Void ratio	k_e	Hydraulic conductivity (m/day)
S_r	Degree of saturation (%)	ρ_a	Apparent resistivity (Ω-m)
wc	Water content (%)	TR	Transverse resistance (Ω-m^2)
ρ_b	Bulk density(mg/m^3)	F	Formation fraction
ρ_{dry}	Dry Density density (g/cm^3)	W	Watts

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1. Introduction

Sub-surface exploration requires engineering and geologic properties of soil. Currently, various techniques are available for assessing the sub-surface properties such as in-situ tests, laboratory testing, and use of geophysical techniques. The various field as well as laboratory testing methods are available for sub-surface characterisation of soil, which has advantages as well as limitations [1]. The application of conventional methods is useful but may not be useful for some unusual cases for effective investigation of subsurface properties [2]. The use of these techniques often lies on the degree of efficiency, applicability, and the nature of work. An assessment of sub-surface properties in the laboratory can be conducted under different conditions. However, actual results may vary in comparison to in-situ test due to disturbed soil samples. Besides, in-situ tests are expensive and time-consuming [3], which impel the researchers to focus on other efficient and alternative techniques such as geophysical techniques. A commonly adopted geophysical technique preferably used as an alternative to conventional techniques is the electrical resistivity method [4]. It is cost-effective, non-destructive, sensitive, and comparatively required less time than conventional techniques [4; 5; 6, 7; 8; 9] since its inception in early 1920's several improvements on this method were made such as three dimensional (3-D) and four-dimensional (4-D) surveys in complex geology. Electrical resistivity methods have received potential attentions in various areas such as mineral exploration [10; 11; 12], archaeology [13; 14; 15], hydrogeology [16; 17; 18], and environmental engineering [6; 19; 20]. A combined use of electrical resistivity method and other conventional techniques are also investigated by several researchers in various areas [21; 22; 23; 24; 25].

Sub-surface soil parameters are well-correlated with electrical resistivity. In other words, electrical resistivity is a function of subsurface soil parameters that includes nature of solid constituents such as distribution of particle size and mineralogy; voids arrangement such as porosity, connectivity and distribution of pore size; degree of saturation of water that is water content, solute concentration and temperature [5]. Electrical resistivity of sub-surface soils varies both in vertical and lateral directions, which can be intercepted by electrical resistivity tomography (ERT) [17]. All such parameters influence the electrical resistivity in different ways and to varied extents. Hence, electrical resistivity provides a good interlinked with engineering properties on various soil index such as Atterberg's limits, dry density, saturation limit of compacted clays, and percentage composition of fine and coarse particles, and hydraulic conductivity [26; 27; 28; 29; 30]. In this work, critical reviews were made on various subsurface soils properties and resistivity trends on soil index using the electrical resistivity method.

1.1. Methodology Outline for Review Process

Data on the utilization of electrical resistivity for sub-surface hydro-geophysical investigation were gathered from some refereed studies that were critically chosen for this study. In total, 82 peer-reviewed works including review articles, research articles, handbooks, and theoretical presentations were employed in this study to report on the systematic review. The research that has been peer-reviewed is from various reputed institutions and organisations that were conducted utilizing electrical resistivity as well as laboratory tests, by considering various soil types of sub-surface strata, densities, and porewater resistivities as well as temperature and other factors. Figure 1 displays the review method's general organisational structure.

Electrical resistivity (ER) method quantifies the potential field generated by current flowing into the sub-surface where contiguous contrast of electrical resistivity is measured.

2. Basic of Electrical Resistivity

The resistance offered by the unit cube material against the current flow through it normal surface is defined as resistivity. If L represents the length of the conductor and A is the cross-sectional area, then the resistance (R) can be defined mathematically as:

$$R = \rho(L/A) \tag{1}$$

Here, ρ is the constant of proportionality known as resistivity or electrical resistivity (ER). It has a unit of ohm-meter (Ω-m). Ohm is defined as the resistance offered by the conductor to produce 1 volt as potential difference after supplying current of 1 ampere. Typically, the concept of Ohm's law is used in electrical resistivity technique, mathematically defined as:

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

where I denote the electric current through the conductor, V represents the voltage, whereas resistance is denoted by R. In particular, R is applicable only for a measurement in a particular circuit and ρ represents the intrinsic property of all physical materials. However, for half-space geometry, we used another term for ρ known as apparent resistivity(ρ_{ap}), defined as:

$$\rho_{ap} = 2\pi d \frac{\Delta V}{I} \quad (3)$$

where $2\pi d$ is for half-space geometry with d denoting inter-electrode spacing in metre (m). The measured voltage across the inner electrodes is ΔV for the specific value of d. Table 1 shows the range of resistivity value compile after Telford et al. [31] and Reynolds [32] for dissimilar materials.

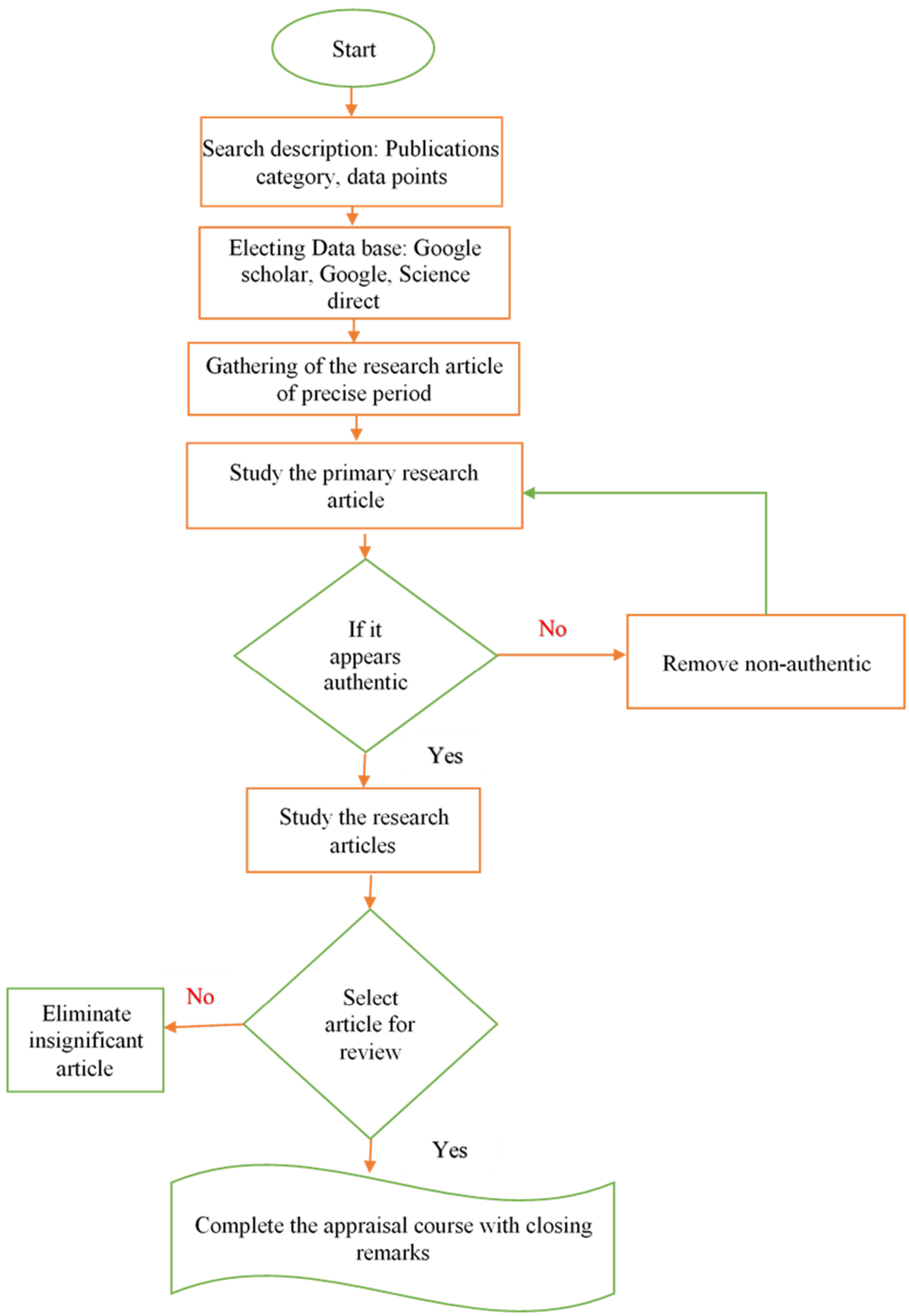

Figure 1. Structure outline of the method for review.

Table 1. Range of resistivity for different materials (compiled after Telford et al. [31] and Reynold [32]).

Material	Min range of resistivity (Ω-m)	Max range of resistivity (Ω-m)
Gravel	100	400
Sand	100	5000
Clay	1	100
Granite	5000	10^6
Gneiss	100	1000
Schist	100	10000
Ground water	10	300
Ice form in sub-surface	1000	10^6
Glacier ice	10^6	10^8
Air	Infinite	Infinite
Limestone	0.067	1

In general, for sub-surface formations, four electrodes are used for measuring the resistivities. Depending on the purpose of sub-surface exploration, different electrodes arrangements were made to measure the potential difference. Figure 2 shows typical resistivity array configuration with AB representing current electrodes and MN representing the potential electrodes. The pole-pole array consists of only single current electrode and potential electrode (A and M). For pole-dipole arrangement, it consists of single current electrode (A) with two potential electrodes (AB), and for dipole-dipole arrays configuration, it consists of both current electrodes (MN) and potential electrodes (AB). Among these electrode configurations the Wenner and Schlumberger arrays configurations (shown in Figure 2) are used widely. The Wenner configuration involves the placement of four electrodes including current (M and N) and potential (A and B) electrodes at equally spaced distance termed as d as shown in Figure 2. Thus outer electrodes cover a distance of 1.5 times d from mid-span in Wenner array. The ρ_{ap} value can be calculated using Equation 3. In Wenner array, d is increased by steps to measure the desired depth.

The spacing of current electrodes (M and N) is equal to five times or more as compared to potential electrodes (A and B) as per schlumberger arrays configuration. In Figure 2, d represents the inner electrodes distance, whereas L denotes the outer/current electrodes distance. Thus in Schlumberger arrays configuration, the ρ_{ap} value can be calculated as:

$$\rho_{ap} = \pi R \frac{(L/2)^2 - (d/2)^2}{d} \quad (4)$$

$$if\ L \gg d$$

$$\rho_{ap} = \pi R \frac{(L)^2}{4d} \quad (5)$$

$$if\ L > 5d$$

2.1. Field investigation

Two commonly used field investigations for sub-surface soils using electrical resistivity method are the resistivity depth sounding method and profiling method. Figure 3 shows the structure outline of the electrical resistivity method.

2.1.1. Resistivity depth proving (or sounding) method

This method (also known as vertical electrical sounding) is used whenever the depth section of a particular place is required. In this method, the depth of influence under the sub-surface is directly proportional to the space between current electrodes at fixed centre. The higher spacing between current electrodes allows deeper penetration of current below the sub-surface, which helps in extracting the characteristics such as depth, thickness, and resistivities. Both the Wenner and Schlumberger configurations are suited to this technique; however, Schlumberger has some advantages. The use of Wenner configuration is more convenient to compute and interpret but it requires lateral length and has limitations. Similarly, the Schlumberger method is easy to use but difficult to interpret [33]. The naturally developing self-potential in the sub-surface is to be eliminated and nullified. Thus only the potential difference developed by experimental impressed current should be considered.

On a double logarithmic scale, the plot between apparent resistivity and current electrode spacing is developed, which is known as sounding curve. To get the layer parameters, the information sounding curve is interpreted. Two commonly interpretations techniques are (a) direct method and (b) indirect method. The direct method employs the computer codes for extracting the layer parameters from the field. The received field curves usually may differ from the available master curves. In such case, the proper layer parameters are opted from the theoretical sounding curve that fits best with the field condition. Direct method of interpretation can be found in the works of Pekeris [34]; Koefoed [35]; and Loke [36]. In later methods, the theoretical master curves prepared in advance with different known layer parameters are compared with the field curves. Several albums of master curves developed for interpretations adopted in the studies of Compagnie Generate de Geophysique [37]; Orellana and Mooney [38]; Rijkswaterstaat [39]; and Flathe [40]. Besides, Sankar Narayan and Ramanujachari [41], and Baig [42] developed 'inverse slope' and 'direct slope', a new method to determine layer thickness and absolute resistivity.

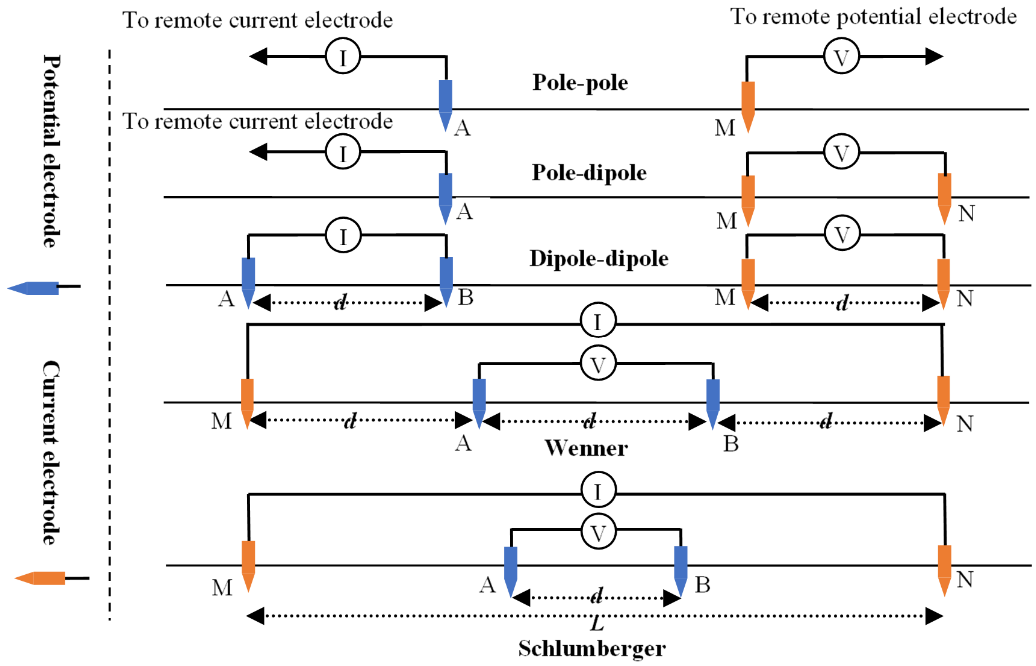

Figure 2. Typical array configuration.

2.1.2. Resistivity profiling (or traversing) method

In this method, the electrode system moves as a whole from one station to another along a line known as traverse or profile. The electrode separation is kept fixed for two to three values ($say\ d = 5\ m, 10\ m, 15\ m\ or\ 20\ m$), and the centre of the electrode spread is moved from one station to another station or grid points to have the same constant electrode points. The main objective in this method is to detect the sub-surface changes in horizontal or lateral spread. On completion of apparent resistivity observations on all the stations, the linear maps or resistivity contour maps of the area showing iso-resistivity lines are prepared. This method is greatly useful for mineral and groundwater exploration where isolated bodies of anomalous resistivity are required.

3. Variations of Electrical Resistivity with Sub-surface Properties

3.1. Effect of water content (wc)

The value of resistivity is affected by the water content present in the soil strata, and they are inversely proportional to each other. The increase in wc present in the void spaces of soil led to decrement in the electrical resistivity [43; 44; 22; 45; 46; 28; 4; 47; 48; 49; 50]. Such studies involve the correlation analysis between electrical resistivity and soil properties (wc, k, ρ_b, etc) with the measurement of field and laboratory resistivity survey. Siddiqui and Osman 2012a measured the electrical resistivity of a different type of soil (silty-sand, sandy, coarse-grained sandy soils) in the laboratory condition keeping the potential difference ranging (30-90V) and temperature of 24 °C. The various parameters such as saturation conditions, difference in temperature, and overburden pressure are responsible for the variation in between field and laboratory resistivity values [51]. Effect of wc for other soil conditions such as metal-contaminated soils, coarse grained clayey sandy soils, and composite end-product of weathering rock has been studied in the works of Chu et al. [52]; Bery and Ismail [53], and Akintorinwa and Oluwole [54].

Cosenza et al. [22] observed that variation in vertical wc contributes virtuous support to identify variations of vertical geotechnical property of the sub-surface. They further conclude that investigation in view of wc can be well-intercepted by electrical resistivity method. In the case of sandy soil, Pandey et al. [55] found that the electrical resistivity decreased rapidly with the increase in water content. They conclude that both relative density and wc can be effectively used to predict electrical resistivity. Rezaei et al. [56] established an inverse correlation between ER and wc indicating that with the decrease in one parameter the other parameter increases. They made a case study of Nargeschal Province, Iran, through geotechnical and geophysical investigation. Sun and Lü [57] in their study found that silty-clay soil with specific wc offers insignificant electrical resistivity than the silt soil. Hence, the obtained correlations have been made with field data, laboratory testing, different soil materials, different densities, different porewater resistivities, temperature, etc. Figure 4 shows data fitting (power, polynomial, and linear relationships) between ER and wc observed by several authors.

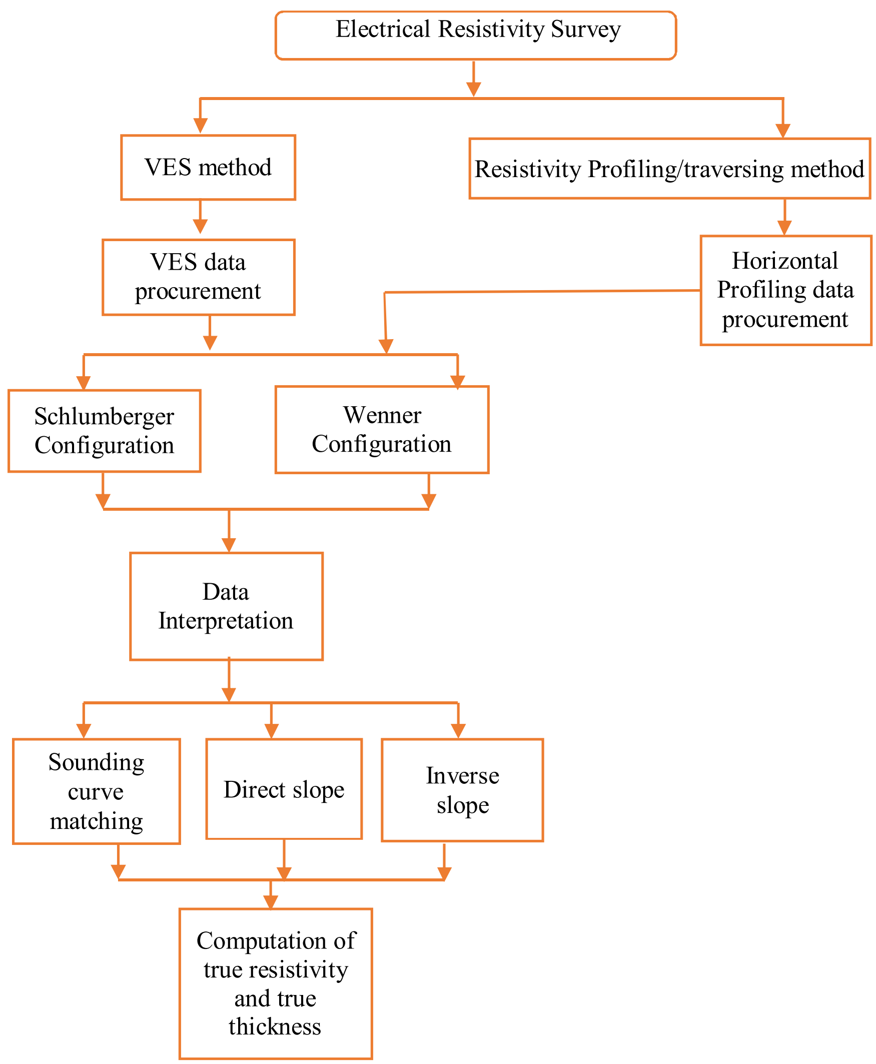

Figure 3. Structural outline for electrical resistivity method.

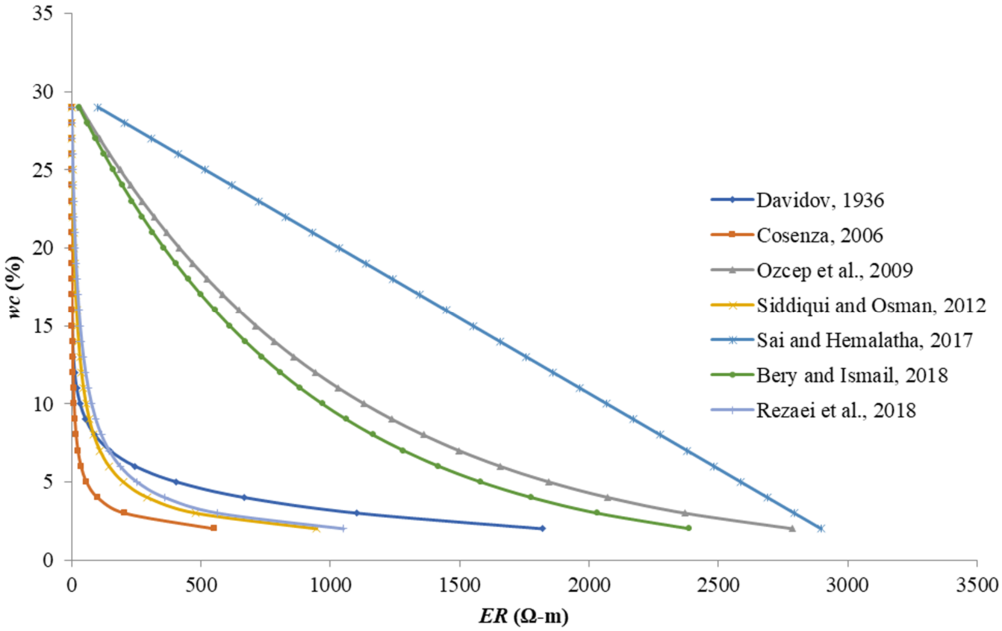

Figure 4. Data fitting between relationship between ER and wc (%).

3.2. Effect of thermal conductivity

A very limited work is noticed related to the relationship between thermal conductivity and electrical resistivity of the sub-surface. Both electrical resistivity and thermal conductivity depends on the distribution, saturation, grain size, and dry density of the soils. Wang et al. [48] analysed a laboratory case study to evaluate the relationship among thermal conductivity (k) and ER (Figure 3). They observed that excluding soil saturation both thermal conductivity and electrical resistivity correlates linearly. They observed that for a well-graded soil both thermal conductivity and electrical resistivity increase with the increase in saturation until a critical value is reached where it becomes stable. Sun et al. [58] performed an experimental study on silty clay soil considering frozen and unfrozen soil conditions to analyse the correlation of thermal conductivity and electrical resistivity. Their study was based on different water contents where the variations of ER with thermal conductivity are discussed on three phases-freezing prophase, freezing metaphase, and freezing anaphase. Figure 5 represents the plots of ER as related to k(W/m.K) considering a temperature of the range 10 °C to 20 °C.

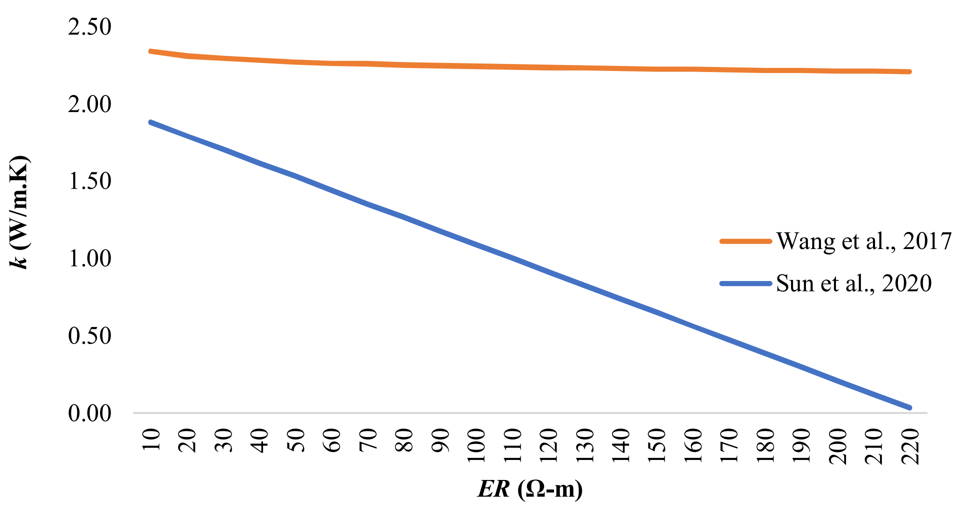

Figure 5. Significant negative correlation between k of soil sample and ER.

Few studies have done for the direct correlation analysis between thermal conductivity and electrical conductivity of soil. Due to the difficulties of a direct relation, Schwarz and Bertermann [59] have investigated modular approach on mediate relationship between thermal conductivity and electrical resistivity. They considered sandy, silt loam, and clayey soil types where thermal conductivity, electrical resistivity, bulk density and wc are determined after each configuration. The authors declare that although there is no direct relationship between thermal conductivity and electrical resistivity yet their mediate correlation can be useful for ER measurements to verify shallow geothermal system.

3.3. Effect of bulk density (ρ_b) of soil

Bulk density increases with the amount of soil compaction, which in turn reduces the volume of larger pores and thereby affects the physical properties [60; 61; 62]. Figure 6 (Abidin et al. [63]) shows the correlations between ER and two types of soil conditions namely-silty sand and clayey soil. They performed a laboratory analysis on disturbed soil samples under control environment (with known temperature and humidity) with the aim to reduce ambiguities (or black box) to determine the relationship between electrical resistivity and physical properties of the soil. The authors give special reference to density, moisture content, and soil grain size. They concluded that the relationship between electrical resistivity and ρ_b followed a curvilinear trend, and suggested that with the higher ρ_b value, there is decrement of electrical resistivity. The derived mathematical relationship for the ρ_b value is summarized in Table 2.

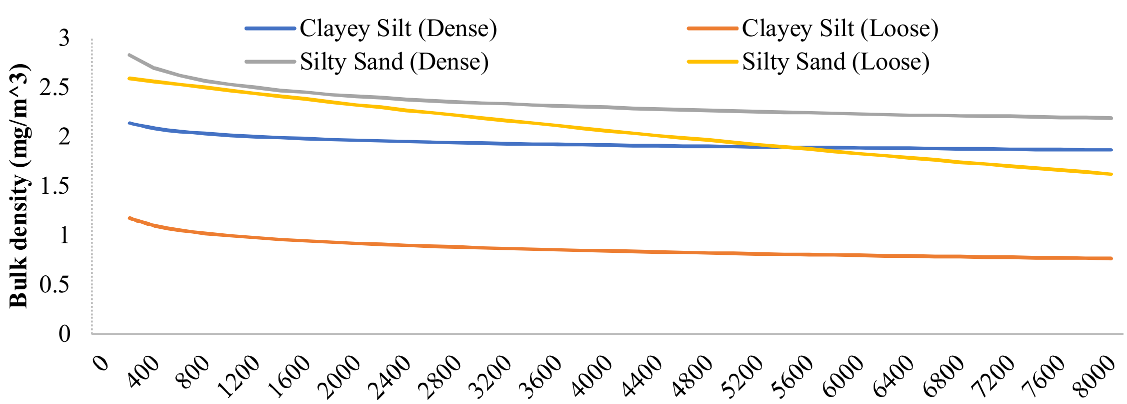

Figure 6. Correlation between bulk density (ρ_b) and ER for silty sand and clayey silt.

Roodposhti et al. [64] conducted a laboratory electrical resistivity test on soils with different compaction and water content. The authors declare that with the increase in density the electrical resistivity significantly decreases, and typically for gravimetric wc with a value less than 0.25. Overall, in the field, compaction assessment is still a matter of considerable debate as it depends on complex factors.

3.4. Effect of Atterberg's limit

The Atterberg's limit describes the critical water content of the soils, which includes shrinkage limit, plastic limit, and liquid limit. Accordingly, a soil may appear in four states namely solid, semi-solid, plastic, and liquid. Geotechnical investigations consider field tests and laboratory tests (e.g. Atterberg's limit, specific gravity, moisture content, permeability, particle size analysis, etc.). An inverse relationship is obtained between apparent resistivity and Atterberg's limit [54; 56]. They conclude that a very weak relationship is established between electrical resistivity and plastic limit, plasticity index, shrinkage limit, and liquid limit. The empirical relations between apparent resistivity and Atterberg's limit and other geotechnical parameters are presented in Table 2. Strong correlation between ER and Atterberg's limit has been obtained by Naseem et al. [65]. Previous studies of Giao et al. [66]; Long et al. [67], and Siddiqui and Osman [51] also claimed to obtained a weak correlation between apparent resistivity and plasticity index.

3.5. Effect of standard penetration test (SPT) value

The standard penetration test is one of the most popular techniques designed to provide information on geotechnical properties of soil. The termed is coined by Karl Terzaghi in 1947 where the actual partial assemblage is already in use in late 1920s by Gow Division of Raymond Concrete Pile Company under the Direction of Harry Mohr. The electrical resistivity value increases with the increase in SPT-N values [68; 69; 7; 70; 24], where N represents standard blow counts. Rezaei et al. [56] made a case study at Nargeschal Landslide zone and obtained an empirical relation between N values of SPT and the resistivity, as reflected in Table 2. The authors concluded that electrical resistivity increased with the increase in the SPT-N values. Figure 7 shows the trend obtained among ER and values of SPT. It is experienced that ER almost linearly increases with the increase in SPT-values.

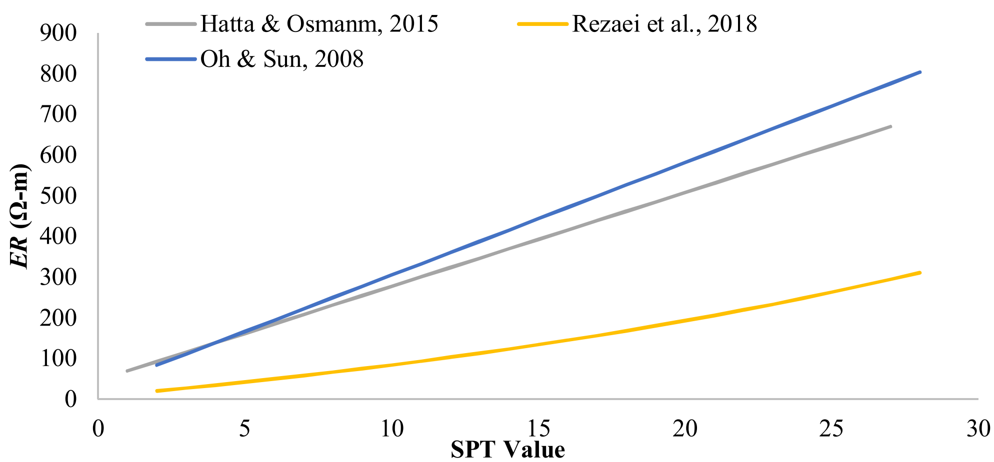

Figure 7. Correlation between SPT-value and *ER*.

3.6. Effect of aquifer hydraulics parameters

The interrelationships between aquifer parameter that is hydraulic conductivity (k_e) and Transmissivity (T_e) as related to ER can be expressed from two well-known fundamental laws –Darcy's law and Ohm's law. Darcy's law designates the concept of fluid flow [71], defined mathematically as:

$$Q = k_e iA \quad (6)$$

Here, Q is the discharge (m^3/s), and i the hydraulic gradient. Ohm's law, on the other hand, designates the concept of current flow, and the differentiated form of Ohm's law can be written [71] as:

$$\sigma = J/E \quad (7)$$

Here, σ denotes the electrical conductivity representing the inverse of ER (i.e. $\sigma = 1/ER$) for homogenous and isotropic medium, E is the applied electric field, and J is the current density (A/m^2). Now considering a prism with unit cross-sectional area, T_e can be expressed in terms of transverse resistance (TR) and longitudinal conductance (L_c) [72] as:

$$T_e = k_e \sigma TR \quad (8)$$

and

$$T_e = (k_e/\sigma) L_c \quad (9)$$

Here, the parameters TR and L_c are also known as Dar Zarrouk parameters [73; 74].

Batte et al. [75] investigated aquifer parameters with ER at Basement Complex of Nakasongola District, central Uganda. A correlation between TR with T_e has been established [76; 77]. The extrapolation of k_e and T_e has been done with the use of surface resistivity, which provides the estimated empirical relation as shown in Table 3. Halihan et al. [78] applied the technique of electrical resistivity to analyse the temporal distribution of potassium permanganate. The authors validated that electrical resistivity technique provide a quantitative assessment of k_e and enable to track the initial direction of inject movement. Similarly, Singh and Singh [79] examined k_e and T_e at coastal aquifers of Tuticorin, Tamil Nadu. The authors divide the area into three major geological formations (Archean, Tertiary, and coastal sediments). Available VES data is then interpreted to determined true resistivity and thickness of the aquifer. The authors also estimated the empirical relationship of aquifer parameters and ER (shown in Table 3). Aleke et al. [80] estimated the formation factor (F), k_e, and T_e. They estimated the empirical relations between ER and hydraulic parameters (Table 3). The authors conclude that both aquifer thickness and resistivity delineated from resistivity data are used to estimate F, k_e, and T_e whereby porosity (n) and tortuosity are estimated. An integrated ERT technique is adopted by Hasan et al. [81] to investigate the geological formation and groundwater potential in hard rock weathered areas. The authors suggested that low ER value in 2D ERT model along each profile provide evince saturated fractures/faults zones that point to presence of groundwater. According to the Singh [82] research work, the permeability of hard rock and alluvium aquifers systems varies exponentially with resistivity.

Figure 8 shows the obtained correlations of hydraulic conductivity (k_e) as related to ER by several authors. The plot shows left skewed towards left top indicating diminishing effect of ER with increased in k_e. Figure 9 shows the plots between T_e and TR, indicating positive correlations between the two parameters.

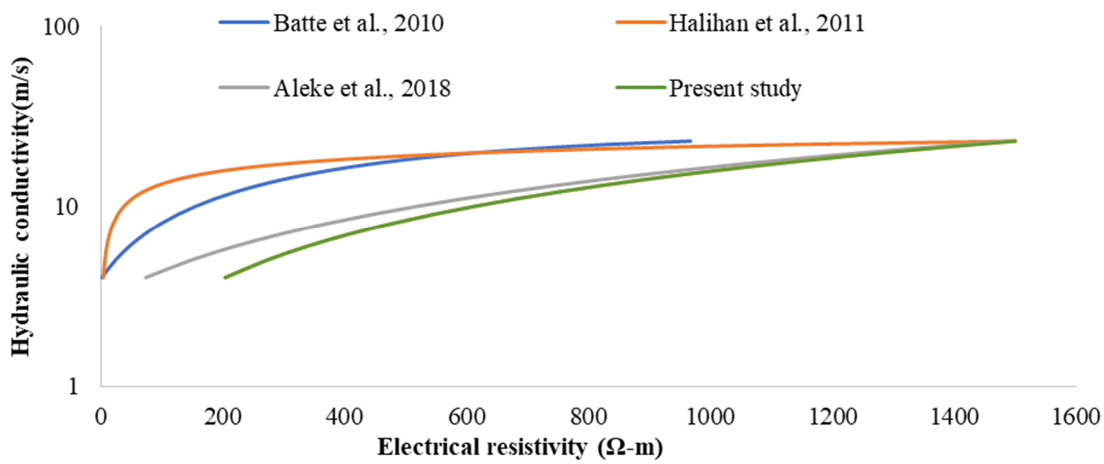

Figure 8. Correlation between hydraulic conductivity (k_e) and ER.

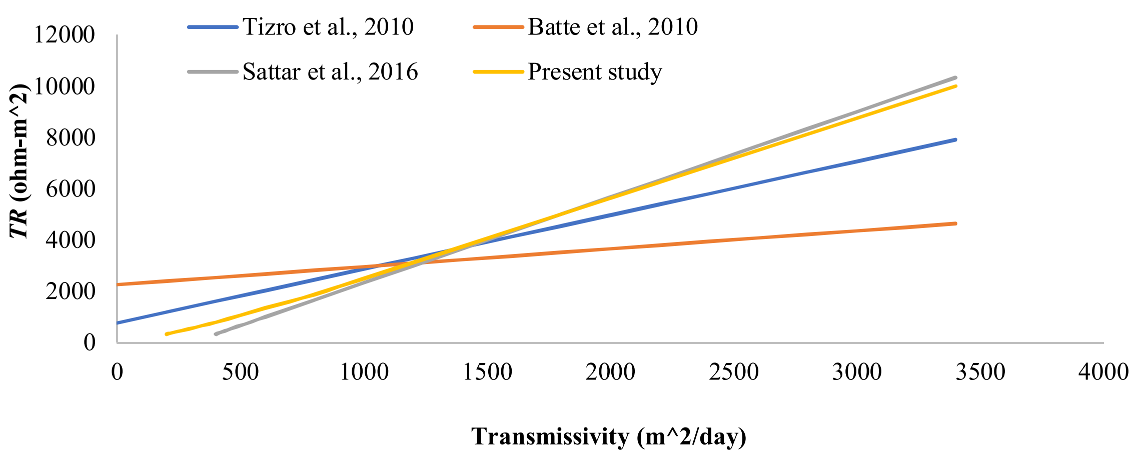

Figure 9. Correlation between transmissivity (T_e) and TR.

4. Discussions

Several important soil parameters and aquifer hydraulic parameters correlating ER for different formations are summarized in Table 2 and 3. The correlation outlined in Tables 2 and 3 provides close agreement among the authors to a certain degree; however, due to site specific, the results rather vary from regions to regions depending upon the soil conditions. In addition, these correlations may be applicable to an extent where data is limited. Nevertheless, it is suggested to verify the acceptability of these correlations through further experimental and theoretical studies.

Table 2. Correlation of various sub-surface parameters and electrical resistivity.

Parameters	Correlation with ER	Soil type	R^2	Reference
wc	$wc = a/ER^2 + b$	-		[43]
	$ER = 1.187wc^{-2.444}$	Fine grained soil, unsaturated sandy soil with gravels and top Oolitic limestone	-	[22]
	$wc = 49.21e^{-0.017ER}$	Sandy soil	0.7859	[28]
	$wc = 0.9756ER^{-0.263}$	Silty-sand and sandy soil	0.5625	[51]
	$ER = 4.72\,wc^{-1.28}$	Zn-contaminated soil	0.993	[52]
	$ER = 5.23\,wc^{-1.30}$	Cd-contaminated soil	0.999	
	$ER = 4.31\,wc^{-1.43}$	Pb-contaminated soil	0.999	
	$wc = -0.155ER + 64.77$	-	0.863	[49]
	$wc = 1.46e^{-0.003865ER}$	coarse-grained, clayey, sand & soil	0.934	[53]
	$ER = 2028.2\,wc^{-1.496}$	-	0.68	[56]
k	$k = -0.7755ln(ER) + 4.3301$	clay, silt, & sand	0.7724	[48]
	$k = 1.97 - 0.0088ER$	Silty-Clay	0.89	[58]
Φ	$\Phi = 39.187 + 0.001p - 61.336\,wc$	-	0.45	[51]
	$\Phi = 0.0985ER + 0.973$	-	0.964	[65]
C	$C = 18.986 - 0.005ER + 14.625wc$	-	0.11	[51]
	$C = 36.569 - 0.1052ER$	-	0.964	[65]
	$C = \frac{ER}{(-0.6898wc^2 + 11.24wc - 47.52)} - \frac{(-2.425wc^3 + 128.3wc^2 - 1610wc + 6189)}{(-0.6898wc^2 + 11.24wc - 47.52)}$	-	-	[64]
SPT-N value	$N = \left(\frac{ER}{3862.72}\right)^{-1.33}$	Rio Claro Formation	$R = 0.30$	[21]
	$N = \left(\frac{ER}{6839.72}\right)^{-0.70}$	Corumbatai Formation	$R = 0.70$	
	$ER = 15.653\,e^{0.034N}$	-	0.70	[56]
K	$ER = 14.104\,K^{-0.047}$	-	0.87	[56]
G_s	$ER = 0.00006\,{G_s}^{13.718}$	-	0.16	[56]
Atterberg's Limit	$ER = 253.73LL^{0.527}$	-	0.06	[56]
	$ER = 100.46\,PL^{-0.292}$	-	0.06	
	$ER = 13.15\,PI^{0.4865}$	-	0.05	
	$LL = -0.0325ER + 50.57$ [For H=0.71]	-	0.52	[54]
	$PL = -0.018ER + 35.21$ [For H=0.38]	-	0.34	
	$PI = -0.015ER + 15.38$ [For H=0.63]	-	0.44	
	$LS = -0.01ER + 9.46$ [For H=0.80]	-	0.73	
γ	$ER = 7.1182\,e^{0.8448\,\gamma}$	-	0.09	[56]
M_c	$M_c = -0.155ER + 64.77$	-	0.863	[49]
q_{bc}	$q_{bc} = 48.44\,e^{0.0083ER}$	-	0.903	[65]
e	$e = -0.042ER + 63.54$	-	0.900	[53]

Table 3. Correlation of important hydraulic parameters and electrical resistivity.

Parameters	Correlation with ER	Soil type	R^2	Reference
k_e	$Log(K_e) = -0.002\rho_a + 2.692$	-	0.614	[75]
	$K_e = 0.3712\, ER$	Composite soil-(medium to Coarse-grained sand, coarse- grained sand with gravel)	-	[77]
	$K_e = -0.022ER + 7.640$	Volcanic and Magmatic/granite bedrock with composites weathered layers.	0.96	[81]
	$k_e = 5E - 8e^{0.0045ER}$	Weathered rock aquifers	-	[82]
	$k_e = 1945.6\, e^{-0.0055ER}$	Intact aquifers		
T_e	$TR = -0.07T_e + 2260$	-	0.609	[75]
	$TR = 2.1T_e + 768.7$	Unconfined alluvial aquifer	0.82	[76]
	$T_e = 0.3079\, TR + 299.81$	Composite soil-(medium to Coarse-grained sand, coarse- grained sand with gravel)	-	[77]
	$T_e = -0.115TR + 415.8$	Volcanic and Magmatic/granite bedrock with composites weathered layers.	0.915	[81]
F	$ER = 279.05F - 133.67$	Sandstone	0.81	[80]

5. Conclusions

From this study, it can be inferred that several studies have been conducted to examine the impact of various sub-surface soil parameters and their relationship to geo-electric conductivity.

It is observed that there is an inverse correlation between ER and wc, and is prominent in sandy soils. The aquifer hydraulic parameters k_e and T_e are well-correlated with ER for different soil formations (clay, silt, and sand, silty-clay). Although ER nearly increases linearly with the increase in SPT-values, other geotechnical engineering properties such as plastic limit, plasticity index, shrinkage limit and liquid limit showed almost nil or low correlations.

Overall, the in-situ tests and other conventional procedures, which are typically expensive and time-consuming, are somewhat overcome by the use of electrical resistivity methodology. This technique incapacitates laboratory analysis of soil samples to a degree where soils samples are barely an undisturbed. In contrast, precise interpretations of the observations demand subject-matter expertise and adequate equipment handling to ensure maximal performance. It is noted that the employment of electrical resistivity technique has demonstrated its wide range of applications in numerous fields including environmental engineering, hydrogeology, and the investigation of minerals and archaeology.

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مروری بر رابطه بین پارامترهای هیدروترمو مکانیکی خاک و مقاومت الکتریکی

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چکیده:

با تأکید بر ایجاد ارتباط بین ویژگی‌های هیدرو-ژئوفیزیکی الکتریکی و زیرسطحی خاک، ارزیابی انتقادی از کاربردهای تکنیک مقاومت الکتریکی در کار فعلی انجام می‌شود. به منظور شناسایی ویژگی‌های متنوع خاک زیرسطحی در لایه‌های مختلف، رویکرد مقاومت الکتریکی یک روش ژئوفیزیکی است که به طور گسترده در اشکال مختلف زمین مورد استفاده قرار می‌گیرد. از سوی دیگر، ارزیابی ویژگی‌های هیدرو-ژئوفیزیکی زیرسطحی خاک‌ها، اطلاعاتی در مورد ویژگی‌های هیدرو-ژئولوژیکی و زمین‌شناسی از جمله طبقه‌بندی انواع آبخوان، آلودگی آب‌های زیرزمینی و داده‌های لرزه‌ای ارائه می‌دهد. اکثریت قریب به اتفاق اطلاعات گردآوری شده در این کار ممکن است به محققان کمک کند تا برخی از مسائل اساسی مربوط به هیدرو-سژئولوژی را بهتر درک کنند.

کلمات کلیدی: نظرسنجی ERT، همبستگی‌ها، خواص خاک، ویژگی‌های هیدرولیک.