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Research Article

Measurement of Peat Soil Shear Strength Using Wenner Four-Point Probes and Vane Shear Strength Methods

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The general objective of this research was to measure the peat soil shear strength using Wenner four-point probes and vane shear strength methods. Specifically, the objective of this study was two-fold, namely, (a) investigating the relationship between laboratory soil resistivity and undrained shear strength and (b) determineing the relationship between in-situ soil resistivity and undrained shear strength. Data were randomly collected over six locations in Meranek, Sarawak, for in-situ test and three repetitions for each data were set based on three parameters. The selected parameters were soil density, moisture content, and salinity for both laboratory and in-situ test using Wenner four-point probes and vane shear method. The soil resistivity and vane shear strength readings for laboratory test were correlated with soil salinity, moisture content, and density. The R^2 values showed a good correlation for soil salinity (R^2 =0.8468) and density (R^2 =0.9475), respectively. However, a weak correlation of R^2 =0.1205 was observed for soil moisture. The R^2 value for in-situ correlation between soil resistivity and three parameters (soil salinity, moisture content, and density) was R^2 =0.8916. It can be concluded that the peat soil shear strengths of the study area using Wenner four-point probes from in-situ were (4.38 ohm.m) and laboratory was (2.47 ohm.m) and when using the vane shear strength method, in-situ was (23 kPA) and laboratory was (5 kPA). This study implies that the peat soil of the study area can be categorized as texture (soft loamy soil) and it is suitable for agriculture instead of construction. The relationship established between Wenner four-point probes and vane shear method can be beneficial for ground engineering design to enhance investigation on site suitability. Future work on DUALEM-421 technique should be emphasised for better subsurface exploration accuracy and resolve peat depth for an in-situ test.

1. Introduction

Field of civil engineering specifically the engineering properties of geomaterials is very crucial since most of tunnels, bridges, and dams are built with a mixed of soils or rocks in it. The most important aspects for the geotechnical engineers to investigate are the strength and the stress-deformation behaviour as well as the fluid flow properties of earth materials; the geotechnical discipline was based on this common framework [1]. There are three categories of common techniques to determine these engineering properties, such as in-situ test, geophysical methods, and laboratory. Geophysical methods were developed because of their accuracy to specify soil properties based on quantification [2].

The laboratory tests have the advantages to measure directly the specified engineering properties under controlled environment and different situation. The samples taken were frequently disturbed during the sampling and drilling processes, which may deviate the actual values of its engineering properties [3]. There are lots of electrical potentials and fields that were often simultaneously observed in natural soil, thus, making it possible to determine which formation correlate with which mechanism [4]. Electrical resistivity and conductivity of soils have been conducted in many research studies and can be divided into three different groups. The first group include laboratory studies of electrical dielectric and conductivity by applying electromagnetic waves at constant rate of different dispersed media [5]. The research helped to form a correlation between electrical quantitative, qualitative, and parameters compositions of electrolytic solutions [6].

Then, the correlation was improved by a research for a constant field with soil electrical parameters [7]. The methods were then developed for groundwaters to calculate electrical conductivity from the solution compositions and for some diluted soil solutions. A study on electrical conductivity of the extracted soil solutions was conducted by [8]. The second group is devoted in studies related to the surface electrical conductivity by using laboratory measurements. The major parameter was the electrical conductivity surface that defines the ion composition and the structure of electrical double layer [9]. Finally, as for the third group of researchers, they are devoted to electrical measurement in their studies on electrical conductivity of rocks, sediments, and soils in-situ with multiple geophysical methods [10]. There are multiple models proposed to define the correlation between electrical resistivity, soil density, shear strength, soil moisture, and soil salinity.

Electrical conductivity, resistivity, and shear strength are commonly measured as electrical parameters in field and laboratory conditions. The relationship between electrical resistivity and soil moisture was measured in both laboratory and field conditions and it will form a curvilinear model; this relationship was proposed by [11]. The water content variations assessment of soil depends on geophysical methods which allowed high spatial extraction and not invasive. There is another technique for electrical imaging known as Direct Current (DC). There is a strong variation shown when using the DC Electrical resistivity; it is principally depending on the soil moisture content of agricultural soil on geotechnical or engineering soils [12]. This research intends to correlate between shear strength of soil and electrical resistivity of a soil by using Wenner four-point probes method and Vane shear test. In this study, our analysis was conducted to a set of graphs that shows the relationships between electrical resistivity, soil shear strength, soil moisture, soil density, and soil salinity.

2. Materials and Methods

2.1. Vane Shear Test. In Norway, Gylland [13] stated that vane shear test has been used as in-situ test equipment since the past years. However, this method tends to be less popular because of CPTU-test. In addition, vane shear data interpretation can cause uncertainty due to its simplicity and be easily affected by its surrounding. In order to improve the quality and reliability of the data, a database was built which consists of parallel vane shear tests and laboratory tests conducted on the samples collected.

This method focuses on undisturbed, undrained shear strength, and stiffness of the soil. The vane shear test was mostly conducted on clay or clayey silts to determine its undisturbed and remoulded shear strength [14]. The instrument is attached to two rectangular plates forming a perpendicular cross; then, the cross will be used to penetrate the ground until its desire depth before applying rotation [15]. Then, torque and rotation are measured and because of its simplicity, it may raise uncertainties regarding installation-effects, equipment, and interpretation.

Atkinson and Richardson [16] stated that geotechnical engineers had a problem with laboratory test to determine shear strength for very soft and sensitive clay because of disturbance from poor quality samplers. The development of vane shear originated from that inconvenient; since then, vane shear was used frequently for geotechnical exploration to determine in-situ undisturbed shear strength from a cohesive soil in saturated soft clay. Vane shear is able to directly measures undisturbed undrained shear strength of soil. Undrained shear strength is defined as a shear condition where the water remained in the soil during the shearing process; the water neither escape from the soil nor absorb into the soil [17]. The water content remains intact during the process. Although vane shear test is quick and simple to determine the undrained shear strength of soil, the data interpretation can be complex. Data collected using vane shear can be easily influenced by its surrounding and could cause reasonable doubts [18]. To reduce uncertainty, researchers must assume that the rectangular blades of the vane shear in the soil and the mobilised shear strength are equal over the surface of rotation at the maximum torque. Furthermore, the natural soil mass is difficult to observe its displacement and failure mechanism whether at field or laboratory. A research conducted by the British Standard [19] attempted to model the failure zone of vane shear test using artificial transparent soil and closer view at the impact towards the formulation of the undrained shear strength.

Blight [20] conducted a lab experiment to determine the soil shear strength; the test was conducted on soft soil by using vane shear because it is the most convenient method to measure shear strength for soft soil and it was less time-consuming. Vane shear can be run in laboratory or in-situ, and it is suitable to determine shear strength for soil with low shear strength, compared to triaxial or unconfined test. Since it can determine the sensitivity of soil, data collected from undisturbed and remoulded soil are important to determine the undrained shear strength, total stress analysis, sensitivity of soil disturbance, and embankment analysis on soft ground stability.

According to Atkinson and Richardson [16], vane shear is a moderately fast in-situ method that can determine undisturbed and remoulded undrained shear strength of soft to moderate stiff soil. The only procedure is by forcing four-blade vane into subsoil stratum and slowly rotating it while measuring its resistant torque. The objective was to determine the shear strength of cohesive soil on an area of interest. The torque is rotated from the handle at a constant rate of 0.1^0 per second; optimum torque forms a relation between optimum shear strength and cylindrical failure surface which include the vane shape and dimension. Vane shear can be conducted either at the bottom of a borehole or directly from the soil surface.

The remoulded shear strength can be retrieved after the vane had been rotated quickly for ten times to remould the soil. Then, the same procedure will be applied to determine the remoulded shear strength. Soil sensitivity (S_t) can be

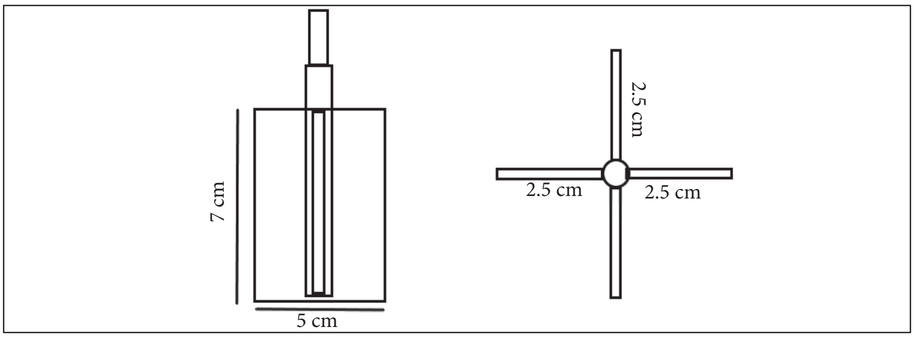

Figure 1: Vane shear design.

calculated as the ratio of the undisturbed and remoulded strength is obtained; however, each test should be separated vertically at least 0.75 m.

For optimum torque (T) measured in the vane shear test will be used to calculate the undrained shear strength (S_u);

$$S_u = \frac{T}{K} \tag{1}$$

Furthermore, the T = torque in N-m or lb-ft and K are constant depending on the dimensions and shape of the vane (m^3 or ft^3), where

$$K = \pi\left(\frac{D^2H}{2}\right)\left[1+\left(\frac{D}{3H}\right)\right] \tag{2}$$

for D and H in meters.

$$K = \left(\frac{\pi}{1728}\right)\left(\frac{D^2H}{2}\right)\left[1+\left(\frac{D}{3H}\right)\right] \tag{3}$$

for D and H in inches.

Blight [20] stated that the calculation for an undrained shear strength by using vane shear needs to be considered because there is no consolidation that has taken place when the vane was inserted or while the test was in progress. Besides that, there should not be any disturbance when installing the vane and there is no progressive failure that could maximise applied torque because it will overcome the fully mobilised shear strength along the cylindrical surface. Then, the presence of isotropic strength in soil mass and remoulded zone surrounding the vane is small.

The advantages of vane shear test are less time-consuming, and it is applicable in homogeneous deposits [13]. The effect of different vane size is minor in most soil and by applying two different vanes with different length to a diameter ratio in the same stratum, the soil strength anisotropy can be inferred [21]. It can determine the properties for sensitive or soft soil, which is impossible to obtain in a laboratory. Figure 1 shows the design used for laboratory and field vane shear test throughout the research.

Vane shear test also has its limitation. An error might occur and could cause an uncertain result outcome. For instance, when there is excessive rod friction, the flaw in torque calibration and the speed of rotation are not constant. Table 1 identifies major errors from the vane shear test. This will disrupt the theoretical nature of the failure mechanism and the correlation between field and laboratory measurements from the same soil will not match.

2.2. Wenner Soil Resistivity. Kearey (2003) conducted an in-situ soil resistivity measurement to observe the corrosion control for buried structures. Resistivity is an electrical resistance between opposite faces of a unit cube of material or known as conductivity. Resistivity uses conductivity as an expression for electrical character of soil that includes water because it is expressed in whole numbers.

Resistivity is defined as a medium to carry electrical currents [22]. However, with the presence of a metallic structure embedded in a conductive medium, the capability of the medium to transfer current will be affected and influenced the magnitude of galvanic currents and cathodic protection currents. In addition, electrode degree of polarisation will also be affected by the amount of currents.

This research applied a method known as Wenner four-electrode, where four metal electrodes will be placed with an equal spacing of separation in a straight line when it is embedded into the soil to a depth not exceeding 5% of the minimum separation of the electrodes [23]. However, the space of separation for the electrode should consider the strata of the soil, because the resistivity will measure the average of a hemisphere of the soil and the radius is equal to the electrode separation.

Furthermore, the voltage between the outer electrode impressed that will cause current to flow, and it will drop between the inner electrodes; then, the voltage will be measured using an accurate and sensitive voltmeter [24]. Resistance can be measured directly; the resistivity, p, is then

$$p, \Omega cm = 2\pi aR = 191.5aR \tag{4}$$

where

a = electrode separation (a in cm)

R = resistance, Ω.

By using dimensional analysis, the unit for resistivity is ohm-centimetre.

Otherwise, when the current-carrying from the outside electrodes is not spaced at equal spacing or interval as the

Table 1: Major source of error in the vane shear test.

Cause	Effect	Influence on Strength Measurement
Damaged zone	Disturbed soil excessively	Decreases optimum strength
Vane rotated too fast	Soil sheared too fast	Increases
Friction between torque rods and soil or casing	Measure torque includes a spurious component of resistance	Increases
Poorly calibrated torque measurement	Inaccurate torque	Increases or Decreases
Test performed in disturbed soil	Soil structure is broken down	Decreases
Isolated gravel/cemented nodules	Measured torque includes a spurious component of resistance	Increases
Unknown sand/silt/shell lenses	Drainage during test	Increases

potential-measuring from the inside electrodes, the resistivity, p, is

$$p, \Omega cm = \frac{95.76bR}{(1 - b/b + a)} \tag{5}$$

where

b = outer electrode spacing, ft,

a = inner electrode spacing, ft,

R = resistance, Ω.

Or

$$p, \Omega cm = \frac{\pi bR}{(1 - b/b + a)} \tag{6}$$

where

b = outer electrode spacing, cm,

a = inner electrode spacing, cm,

R = resistance, Ω.

Other than that, for soil that is contained in a soil box, the resistivity, p, is

$$p, \Omega cm = \frac{RA}{a} \tag{7}$$

where

R = resistance, Ω,

A = cross-sectional area of the container perpendicular to the current flow, cm^2

a = inner electrode spacing, cm.

The spaces between the inner electrodes should be measured from the inner edges of the electrode pins and not from the epicentre of the electrodes as depicted in Figures 2 and 3. Then, the separation between the electrodes is supposed to be equally the same.

This method is applicable for in-situ with appropriate equipment such as voltmeter, an ammeter or galvanometer, four electrodes, and sufficient length of wire to form a connection between the equipment and the soil. The amount of current usually generates is 97 Hz. It is preferred since the use of DC can cause errors to polarisation of most electrodes.

Kalinski and Kelly [25] mentioned that the source of current can be generated from an AC generator or a vibrator-equipped DC source. However, an unaltered AC generator could be used if the electrodes are abraded with bright metal before immersion; polarity frequently reversed while measuring and the measurements are constant for each polarity. In addition, the voltmeter will not influence current from the circuit to avoid polarisation effects. The galvanometer movement type will yield a good result if the meter input impedance is at least 10 mega-ohm.

The selection for electrode depends on the condition and size of the area of interest. Afterwards, the materials need to be heated for it to become firm and rigid when inserted into dry or gravel soils. The electrode has a handle for wire attachment and the complexity of its wiring is 18 until 22-gage insulated stranded copper wire. However, the electrodes should be in great condition to ensure low resistance contact at the electrodes and meter. A shielded multiconductor cable can be formed with electrode permanently located at preferred intervals and the measurement is almost the same for field testing and laboratory testing. Laboratory test electrodes are replaced with an inert container containing four permanently mounted electrodes (Figure 1). The box dimension depends on the requirement for the study; resistivity is read directly from the voltmeter without any calculation. In addition, the box should not be contaminated from the previous sample to avoid any error.

The meter needs to be checked frequently to avoid an error not exceeding 5% and to maintain its accuracy of resistance. If it exceeds the limit, a calibration curve is needed to correct all the measurements accordingly. The soil box can be calibrated by using a solution, for instance, solutions of sodium chloride and distilled water with a resistivity of 1000, 5000, and 10000 Ω.m. It is applicable if the resistivity of the solution was known. The preparation for this solution should be under laboratory condition by using a commercial conductivity meter and, then, calibrated to standard solutions at 20°C.

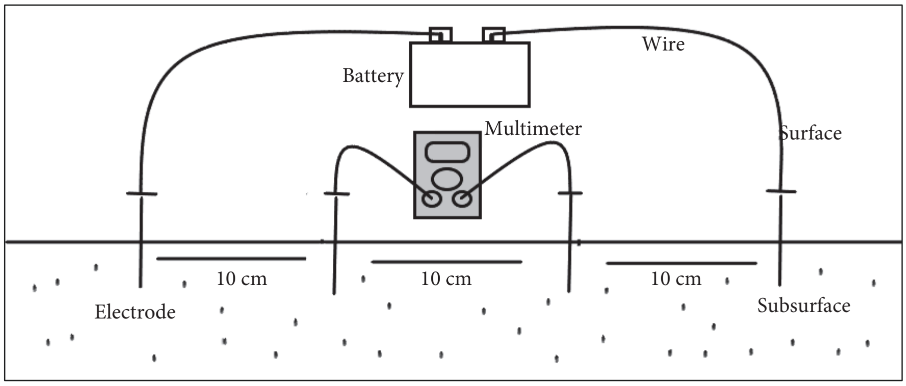

Figure 2: Wenner soil resistivity in-situ test design.

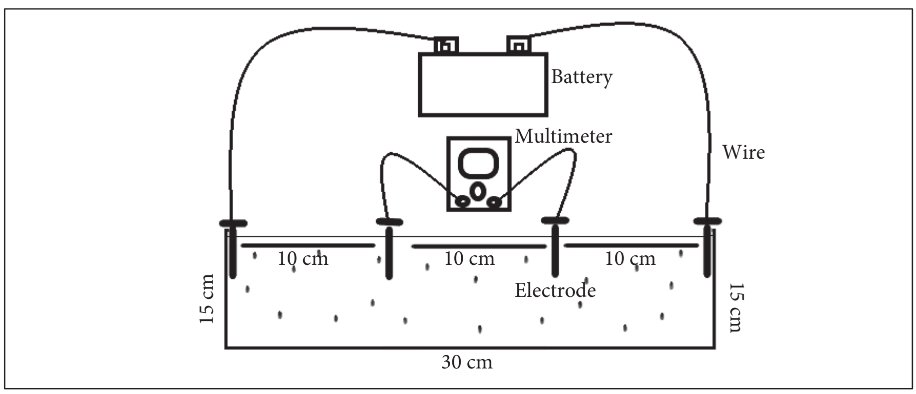

Figure 3: Wenner soil resistivity laboratory test design.

Nayak and Shrihari [26] stated that there is a selected alignment for measurement of an in-situ procedure to include uniform topography over exceeding limits of electrode span. This test cannot run on nonconductive bodies, for instance, frozen soil, boulders, and concrete foundation, because it will not represent soil of interest in electrode span. Then, materials with high conductivity, such as cables and pipes, cannot encounter the electrode span. Furthermore, electrode spacing should be based on the area of interest, because most pipelines are installed at depth from 1.5 until 4.5 m and electrode spacing of 1.5, 3.0, and 4.5 m are frequently used. Electrode spacing should suffice with the maximum depth of interest because calculating field resistivity spacing of 1.58, 3.16, and 4.75 m, which resulted in multiplication factors of 1000, 2000, and 3000, can be used with a DC vibrator galvanometer.

Furthermore, all electrode spacing, resistance or amperes and volts, date, time, air temperature, topography, drainage, or indication of contamination must be recorded for ease during interpretation. During soil sampling it should represent the area where the stratum of interest contains various soil types and all soil needed to be extracted and later create a mixed sample [27]. The soil should be well compacted in the soil box to recreate the same condition as in the study area. This process will eliminate all air spaces.

In addition, resistivity measurement depends on the degree of compaction, moisture content, constituent solubility, and temperature [28]. The effect of various compaction and moisture content can be reduced by saturating the sample before adding into the box. It is prepared by using a slurry stiff of the sample by adding water on top of the water surface until it evaporates before the slurry is remixed and added into the box. However, if there is no access to groundwater from sample extraction to saturate the soil, distilled water is applicable.

By saturating the soil with tap water, the soil resistivity is expected to be less than 10000 Ω.m. Some soil tends to absorb moisture much slower and trapped dissolve constituents longer and does affect resistivity for 24 hours because of unstable saturation. Surplus water can remove soluble constituents if it is mixed with soil.

Besides that, temperature reading calibration is unnecessary if the test was conducted in a ditch or immediately after the sample was taken [29]. However, if the sample remained subsequently, resistivity reading needs to recalibrate if temperature is substantially different from ground temperature. When soil sample temperature exceeds 21°C, correction to 15.5°C is suggested.

$$R_{15.5} = R_T \left(24.5 + \frac{T}{40}\right) \tag{8}$$

where

T = soil temperature, °C,

R_T = resistivity at T°C.

Pozdnyakova [30] stated that soil resistivity is suitable for graphical presentation because we can identify gradients and drastic change in soil condition. There is a method known as cumulative probability analysis; it uses precise mathematical treatment. It intends to determine the probability for soil presence with constant or high resistivity than value because random resistivity is measured on site and it can present a pilot plan or similar layout.

Pedological surveys are applied in planning and interpreting f an extensive survey [31]. The measurements are made for each soil classification under different drainage conditions to ease survey planning. However, if an assessment required a resistivity data for corrosion control measurement, it is suggested that the test used true random basis due to the number of soil sections inspected in which unlimited and infinite population characteristics can be applied to simplify statistical treatment. In addition, an error and risk could be 5% greater than 100 Ω.m and should be suited for most situations and the limit for an error should be 10% of expected mean resistivity. Then, the mean and median value cannot be predicted with accuracy; thus, sampling techniques must be employed. The mean and median for resistivity values are used to determine the corrosivity of the soil [32], when there is a slight change in resistivity with distance and various moisture content and drainage are indicative of severe local conditions. Cumulative probability plots will indicate the homogeneity of the soil over an area and it will indicate the probability of severe, moderate, and minimal corrosion of various construction materials.

The accuracy of a resistivity interpretation results is based on the experience of a researcher [33]. An experienced researcher can recognise the subsurface conditions, where the embedded structures have been implanted. Surface contamination tends to concentrate on existing ditches with surface runoff, then, by lowering the resistivity below the natural level [34]. Besides that, contamination evaluation will be affected when a new route is evaluated, and soil samples can be retrieved at crossings of the existing pipeline and cables by using soil augers.

There are other resistivity measurement techniques, for instance, commonly used two electrodes mounted on a prod that is injected into the soil at the grade of excavation [35]. This method is inherently less accurate than Wenner's four-point probes method because of its polarisation effects. However, to increase reliability, a laboratory investigation can be conducted, and it should refine the results. Overall, all methods consist of precision and bias; the precision was determined by a statistical evaluation of multiparticipant evaluation with each different meter. Wenner's four-point soil resistivity is one of the methods that do not have any bias.

3. Results and Discussion

3.1. Soil Resistivity and Vane Shear Laboratory Test. Based on the data trends, it was shown that the electrical resistivity and shear strength tend to decrease as the soil salinity and soil moisture increase and then it becomes stagnant. However, both electrical resistivity and shear strength data trends increase as the soil density increases and then it tends to become constant. Hence, the equation is shown below.

Soil salinity correlation coefficient:

$$
\begin{aligned}
y &= -1.419 \ln(x) + 12.655, \\
R^2 &= 0.8468 \\
y &= 1.1318 \ln(x) + 3.7589, \\
R^2 &= 0.7031
\end{aligned} \tag{9}
$$

Soil moisture correlation coefficient:

$$
\begin{aligned}
y &= 4.1963 \ln(x) - 25.062, \\
R^2 &= 0.1205 \\
y &= 0.7625 \ln(x) + 7.1639, \\
R^2 &= 0.2127
\end{aligned} \tag{10}
$$

Soil density correlation coefficient:

$$
\begin{aligned}
y &= 12.036 \ln(x) - 71.469, \\
R^2 &= 0.9475 \\
y &= 1.4974 \ln(x) + 3.6914, \\
R^2 &= 0.6713
\end{aligned} \tag{11}
$$

The electrical properties of peat: the soil sample resistivity was affected by soil moisture, soil salinity, and soil density as depicted in Figures 4, 5, and 6. The results of the study proved that the resistivity of peat tends to decrease as the soil moisture and soil salinity increase; however, the resistivity tends to increase as the soil density increases. However, the shear strength of the soil sample was not affected by soil moisture and soil salinity as much as soil density. The results showed that the soil shear strength of peat decreases slightly and then remained stagnant as the soil moisture and soil salinity increase; then, the soil shear strength of peat increases steadily as the soil density increases.

Based on a previous laboratory test that determines the peat degree of humification, it was found that the peat sample can be categorised as H7 because of its highly decomposed faintly recognisable plant structure and the water released was dark and almost pasty.

Furthermore, the results showed that the resistivity of peat was higher as soil density increases (Figure 6) than the increase of soil moisture and soil salinity where the soil resistivity tends to decrease as soil moisture and soil salinity increase (Figures 4 and 5). Despite the fact where a highly decomposed peat supposedly shows low resistivity reading, by increasing the soil density the resistivity will increase.

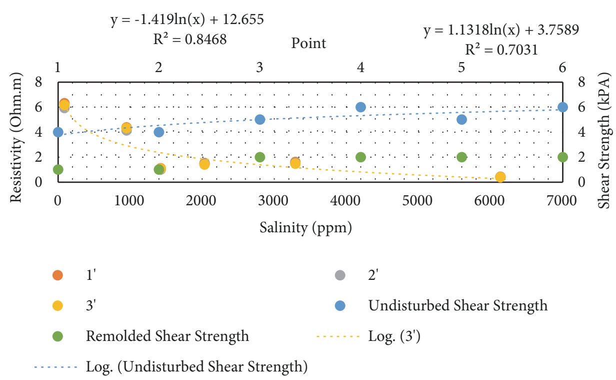

FIGURE 4: Soil Resistivity and soil shear strength vs soil salinity.

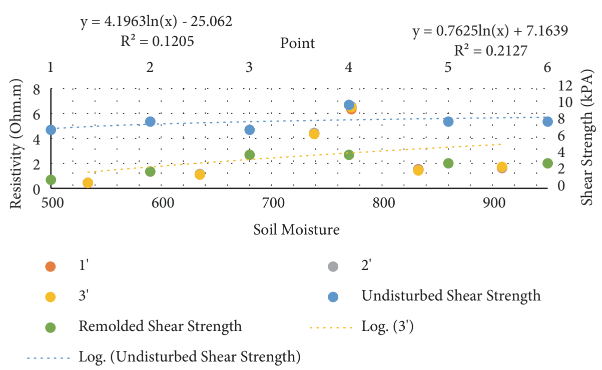

FIGURE 5: Soil Resistivity and soil shear strength vs soil moisture.

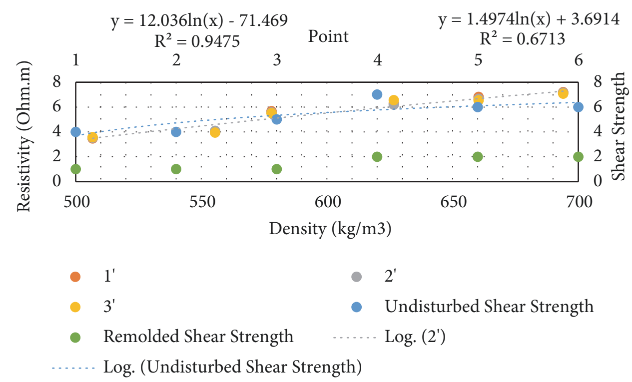

FIGURE 6: Soil Resistivity and soil shear strength vs soil density.

Next, the results showed that the shear strength of peat changed slightly when there is a change in soil density (Figure 6) as compared to soil moisture and soil salinity (Figures 4 and 5). Therefore, as soil density increases the shear strength of peat tends to increase (Figure 6). This study revealed that, to create a firm subsurface foundation for construction, the soils need to be fully compacted where there should not be any presence of air void and water inside a soil medium. These elements, such as water and air, could cause instability inside the soil medium making. The soil tends to slide over itself as the pressure is applied on the soil surface. This study has proven that peat humification could result in a higher resistivity reading because of its high organic matter and when there is an increase in its soil density and soil compaction. Besides that, it also revealed that the resistivity tends to decrease as soil salinity and soil moisture increased and the resistivity tends to increase as soil density increased.

Furthermore, as soil salinity increases the tendency for soil resistivity to decrease is because of the availability of ions in the water (Figure 4). These conductive ions come from dissolved salts that were added to the soil sample. Compounds that dissolve into ions are known as electrolytes. The more ions that present, the higher the soil salinity, thus, the higher the conductivity inside the soil medium making the resistivity of the soil decreased. In addition, ions conduct electricity because of their positive and negative charges, but when electrolytes dissolve in water, it splits into be positively charged known as cation and negatively charged known as anion particles. Electrical conductivity increases as the presence of ions inside the water increases, making the soil resistivity decrease as the soil salinity increased. However, by increasing the soil salinity of peat sample, it does not affect the soil shear strength. The results of the study showed that the shear strength of peat did not decrease but remained constant at a certain point (Figure 4). This shows that the salinity does not contribute much to determine the soil shear strength as much as it contributes to soil resistivity. This is because salinity only increases with the presence of ion rather than organic material that could fill up the voids inside the soil medium to increase its stability and strength. The relationship between soil moisture and electrical resistivity is presented in Figure 5; the result showed that there is a strong curvilinear relationship between soil moisture and soil electrical resistivity for the soil sample collected from Kota Samarahan, Sarawak. The analysis revealed inconsistencies in the resistivity results as the soil moisture of the soil sample increased. This instability limits the effectiveness of electrical resistivity in measuring soil resistivity. However, we have observed the resistivity reading as it gradually increases and at its maximum point it decreases gradually as soil moisture increases in the soil sample. The magnitude of this effect decreased as it became increasingly unstable until a smooth transition occurred for highly unstable flows.

In addition, even in a homogeneous medium, flow instability can be affected by the cumulative effects of capillary, buoyancy, and viscous force [1]. However, soil moisture does not cause much difference for soil shear strength when compared to soil density. The instability only affects soil resistivity rather than soil shear strength. Thus, the shear strength remained constant as the soil moisture increased. Besides that, the study showed that electrical conductivity increased as soil moisture increased, thus making the resistivity decrease as soil moisture increased.

A good understanding of a correlation between electrical resistivity and all three parameters (soil salinity, soil density, and soil moisture) as most peat could be underlying the reasons for tropical peat electrical behaviour. In addition, the peat itself has a negative charge because of organic matter interbedded in the soil medium [36]. The humus produces a negative charge usually formed from the dissociation of H^+ and colloids also known as humus, a chemically active

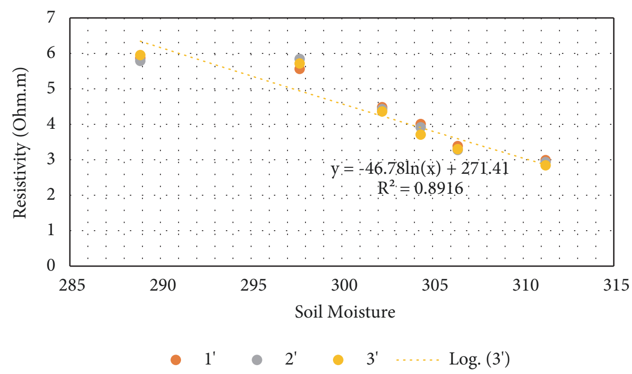

Figure 7: Summarize resistivity data from Line 1 until Line 6 vs soil moisture.

fraction for peat. Furthermore, electronegativity and ions are sourced from a large surface area of its mass and chemical properties and its consistency were physical properties imparted to the peat by humus [37]. When the peat sample has high water content, low organic content, and high salinity and quantity of colloidal particles, it will have resulted in a higher electrical conductivity and lower electrical resistivity. However, that could change if pressure, compaction, and increase in organic content were added to the soil sample. Therefore, peat humification process depends on its biology, enzymes, and chemistry [38]. The breakdown of the plants occurs when there are bacteria, soil microflora, and fungi, thus making the higher contribution of humus contain a higher degree of humification. In addition, the peat will undergo a condition that will affect its soil matrix, where the particle size changes from coarse to finer particles. The humification processes could form more humification when there is an increase in the quantity of the humus particles; thus, it will decrease the resistivity of peat.

3.2. Soil Resistivity and Vane Shear In-Situ Test. According to the data trend results, the soil resistivity decreases constantly as the soil moisture increases. The summarised data (Figure 7) trend for all six locations can be obtained below, and all six-location data trend separately.

Summarize soil resistivity vs soil moisture correlation coefficient:

$$y = -46.78 \ln(x) + 271.41, \quad R^2 = 0.8916 \tag{12}$$

Line 1 correlation coefficient:

$$\begin{aligned} y &= 6.5071e^{0.005x}, \\ R^2 &= 0.6306 \\ y &= -1.077 \ln(x) + 24.927, \\ R^2 &= 0.0105 \end{aligned} \tag{13}$$

Line 2 correlation coefficient:

$$\begin{aligned} y &= -0.576 \ln(x) + 8.0633, \\ R^2 &= 0.4852 \\ y &= -9.052 \ln(x) + 37.472, \\ R^2 &= 0.2642 \end{aligned} \tag{14}$$

Line 3 correlation coefficient:

$$\begin{aligned} y &= 0.2439 \ln(x) + 3.7667, \\ R^2 &= 0.919 \\ y &= -1.447 \ln(x) + 25.386, \\ R^2 &= 0.106 \end{aligned} \tag{15}$$

Line 4 correlation coefficient:

$$\begin{aligned} y &= -0.721 \ln(x) + 6.0482, \\ R^2 &= 0.9398 \\ y &= -1.518 \ln(x) + 22.493, \\ R^2 &= 0.1475 \end{aligned} \tag{16}$$

Line 5 correlation coefficient:

$$\begin{aligned} y &= -0.618 \ln(x) + 5.1637, \\ R^2 &= 0.9784 \\ y &= -0.681 \ln(x) + 25.028, \\ R^2 &= 0.0162 \end{aligned} \tag{17}$$

Line 6 correlation coefficient:

$$\begin{aligned} y &= -0.14x + 5.715, \\ R^2 &= 0.9863 \\ y &= -0.718 \ln(x) + 26.085, \\ R^2 &= 0.011 \end{aligned} \tag{18}$$

On Line 1 (Figure 8) and Line 2 (Figure 9), results showed that the resistivity generally decreases with time after it reaches its maximum resistivity 7.17 Ω.m and 7.60 Ω.m, respectively. Furthermore, the graph for Line 1 showed that high resistive materials are found at 60s until 90s that indicate the electrical conductivity transferred between probes inside the soil medium having trouble passing through the peat particle during the initial probe insertion. However, after the first 90s, the electrical resistivity tends to decrease gradually until 5.87 Ω.m which indicates that the electrical conductivity eventually overcomes the resistancy from peat particle. This shows that peat particle has an instability electrical flow

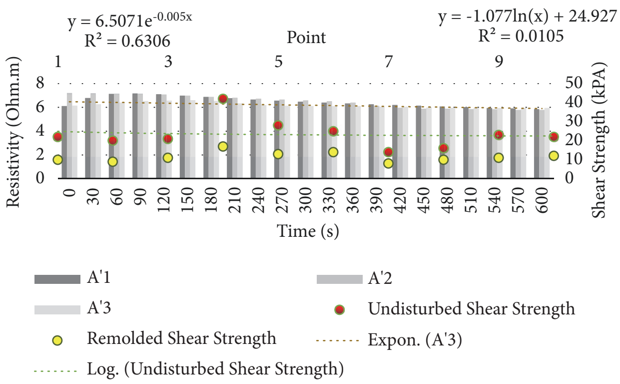

Figure 8: Line 1, in-situ test.

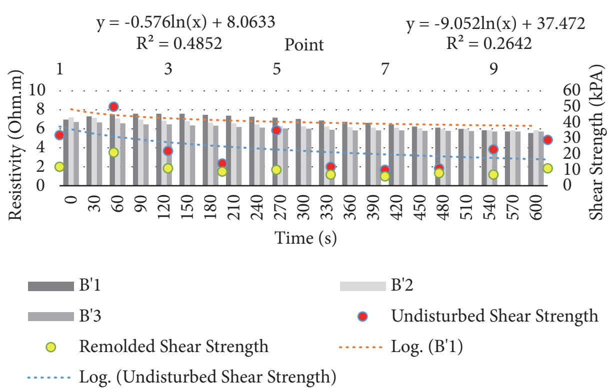

Figure 9: Line 2, in-situ test.

characteristic where it can change with time. However, it is fascinating where the shear strength test result also shows inconsistency, where at depth 0.8 m the shear strength reached its maximum value with 42kPA and, then, gradually dropped from 28kPA until 22kPA with increasing depth. It shows that, for Line 1, the peat shear strength is decreasing with depth and, however, for electrical resistivity also shows a gradual decrease with time.

The electrode spacing for Line 1 was 14.8 cm with its electrical current depth of penetration at 0.74 cm, and the length of the electrode was 2.5 cm. Among these six lines, Line 1 shows the second highest electrical resistivity because it has the lowest soil salinity and soil moisture, meaning that the availability of ions and water support for electrical transferred through soil medium was limited. It can be assumed as one of the firmest and the most stable soil foundation when compared to the other five lines.

Furthermore, the results showed that the resistivity for Line 2 reached its maximum value at 90s. However, it gradually decreased from 7.60 Ω.m until 5.57 Ω.m begins after 90s until at the end of the test. It shows how unstable and inconsistent an electrical conductivity in a peat medium, where it may still have dropped lower than 5.57 Ω.m. The maximum resistivity value lasted for only 60s, meaning that the first 150s the resistant was at its peak until the electrical current was able to pass through the soil particle with ease. However, the results showed that the soil shear strength for

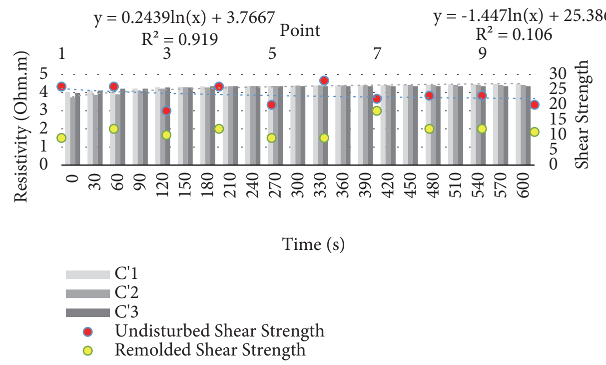

Figure 10: Line 3, in-situ test.

Line 2 reached its maximum value at depth 0.4m with 50kPA and, then, gradually decreased to 14kPA at depth 0.8m. Then, the shear strength was slightly increased to 35kPA at depth 1.0m because there was a root tangled at the tip of the vane and it created a false shear strength reading.

After burrowing deep into the soil medium, the peat shear strength tends to decrease gradually at depth 1.2m until 1.6m with 12kPA and 11kPA, respectively. Suddenly at depth 1.8m and 2.0m with 23kPA and 29kPA, respectively, the shear strength increases drastically. After extracting the vane from the soil medium, it can be observed that there are lots of slightly decompose roots tangled around the vane, wrapped around the vane making it harder for the torque to be twisted, thus, resulting a high value of shear strength. The electrode spacing for Line 2 was 14.8 cm with its electrical current depth of penetration at 0.74 cm, and the length of the electrode was 2.5 cm. Line 2 has the highest electrical resistivity reading with 7603.39 Ω.m and higher soil salinity and soil moisture 94 ppm and 297.67, respectively, compared to Line 1. Even though Line 2 has higher soil moisture and soil salinity compared to Line 1, thus, the resistivity result for Line 2 is supposedly lower compared to Line 1. However, Line 2 resistivity reading was slightly higher because based on field observation when extracted the vane from soil medium, there were lots of organic materials attached and tangled to the vane.

It can be assumed that the organic material had influenced the electrical conductivity making the resistivity reading higher because the electrical resistivity tends to increase with increasing organic materials. Line 3 (Figure 10) however, showed a consistent increase for electrical resistivity reading, but a sinusoidal motion for shear strength reading. The result showed that the electrical resistivity reading becomes stagnant as it reaches 180s with 4.35 Ω.m and steadily increase until the 600s with 4.49 Ω.m, meaning that the electrical current travel through the soil medium was much more stable compared to Line 1 and Line 2. However, the soil moisture and soil salinity for Line 3 was the highest value compared with the other lines with soil salinity, 1285 ppm and soil moisture, 3.02. This indicates that the soil medium contains a high amount of ion that helps to carry the electrical current travel through the soil medium resulting in lower soil resistivity reading compared to the other lines.

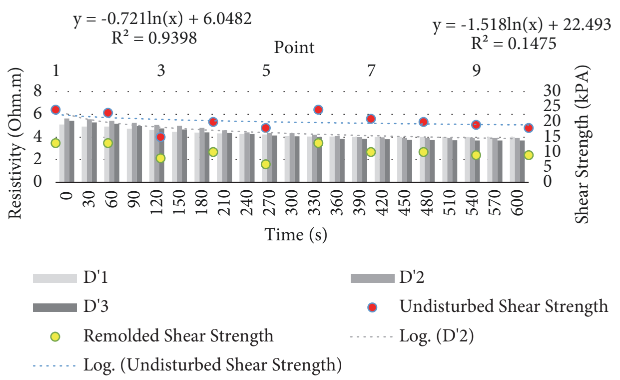

Figure 11: Line 4, in-situ test.

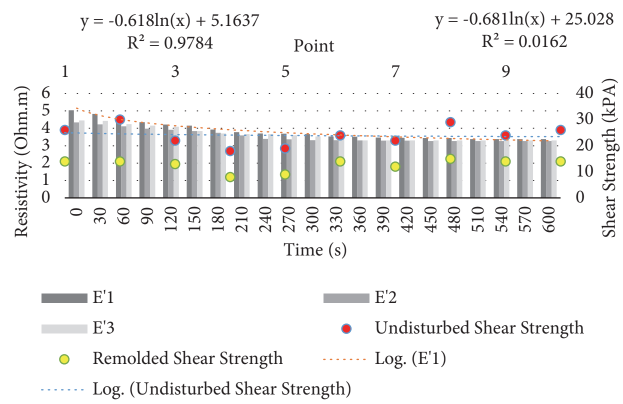

Figure 12: Line 5, in-situ test.

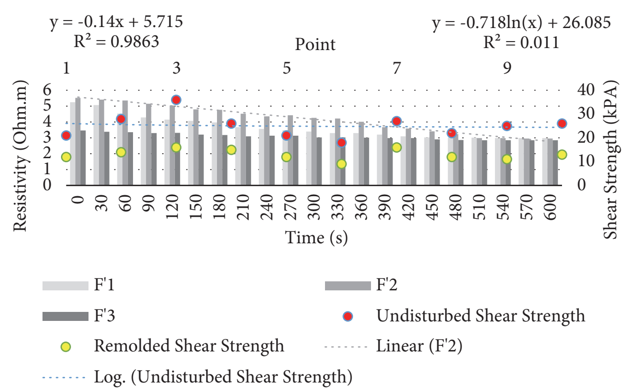

Figure 13: Line 6, in-situ test.

The soil was also well saturated (Figure 10), resulting the torque to twist with ease and ended up with a lower soil shear strength with average 23.2kPA, while Line 1 and Line 2 are with average 23.3kPA and 23.8 kPA, respectively. In addition, during the extraction of vane shear for Line 3, it was observed that there is no presence of roots attached at the tips of the vane. This indicates that organic material can influence the vane shear test with false soil shear strength data. However, the organic material can also influence the electrical conductivity by blocking the electrical current to passes through the soil medium, thus, resulting in high electrical resistivity reading.

On Line 4 (Figure 11) until Line 6 (Figure 13), results showed that the resistivity generally decreases with time and remained stagnant when it reaches 360s and above with 4.01 Ω.m, 3.92 Ω.m and 3.71 Ω.m for Line 4, Line 5 and Line 6 respectively. The graphs for all three-lines showed none resistive materials that indicate that the electrical conductivity transferred between probes inside the soil medium was not having any problem passing through the peat particle during the initial probe insertion. However, the shear strength reading from all three lines showed an inconsistency that forms a sinusoidal motion. This indicates that the shear strength of a soil is different depending on its depth. In addition, from line 4 until line 6 the peat particle does not show any instability electrical flow characteristic where it remained stagnant for a specific amount of time. Then, Line 5 from Figure 12 shows a slight decrease in resistivity reading until it remains stagnant throughout the test.

However, it is fascinating where the shear strength test result for each line showed the same sinusoidal motion movement and the average shear strength values were not drastically different from each other with 20.2 kPA, 24 kPA, and 25 kPA for Line 4, Line 5, and Line 6, respectively. It shows that for these three lines of the peat shear strength it may show inconsistency with depth; however, for electrical resistivity reading it shows a gradual decrease and then remained constant with time. The electrode spacing for Line 4 until Line 6 was the same setup as the previous line with 14.8 cm and its current depth of penetration at 0.74 cm and the length of the electrode was 2.5 cm. Then, compared to all the previous lines, Line 2 shows the highest electrical resistivity because it has the lowest soil salinity and soil moisture, meaning that the availability of ions and water support for electrical transferred through soil medium was limited. It can be assumed as one of the firmest and the most stable soil foundation when compared to the other lines.

Line 4 until Line 6 showed a consistent decrease for electrical resistivity reading and a sinusoidal motion for shear strength reading and vice versa in comparison to Line 3. The result showed that the electrical resistivity reading becomes constant as it reaches 360s and above for all three lines with 4.01 Ω.m, 3.92 Ω.m, and 3.71 Ω.m for Line 4, Line 5, and Line 6, respectively. This indicates that the electrical current was travelling through the soil medium with ease compared to Line 1 until Line 3 because it was measured that the value for soil salinity and soil moisture from Line 4 until Line 6 increases. It shows that when the soil medium contains a high amount of ion, the ion will help to carry the electrical current travel through the soil medium that will result in low soil resistivity reading compared to the previous lines. Hence, Line 3 until Line 6 were assumed as the less stable soil foundation compared to the other lines since they have low electrical resistivity and the lowest soil shear strength making them the most vulnerable and less compacted.

4. Conclusion

The results showed that by using a Wenner four-point probe vane shear strength method is able to determine the shear strength of a soil. Then, both soil resistivity and vane shear strength were correlated with three different parameters produced a good correlation coefficient with R^2 =0.8916 and formed a linear relationship, which decreases as the soil salinity and soil moisture increase, and then it tends to increase with the increase of soil density. The results indicated in both laboratory and the in-situ test showed the same pattern for correlation coefficient were as follows: laboratory soil salinity (R^2 =0.8468 and form a nonlinear relationship), density (R^2 =0.9475 and form a linear relationship), and moisture content (R^2 =0.1205 and form a curvilinear relationship). In-situ Line 1 (R^2 =0.6306), Line 2 (R^2 =0.4852), Line 3 (R^2=0.919), Line 4 (R^2 =0.9398), Line 5 (R^2 =0.9784), and Line 6 (R^2 =0.9863), where electrical resistivity tends to increase as soil density increases and then it tends to decrease as soil salinity and soil moisture increase. However, the soil resistivity values between laboratory and in-situ test were slightly different as follows: laboratory soil salinity (2.47 ohm.m), density (5.53 ohm.m), moisture content (2.58 ohm.m), and in-situ (4.37 ohm.m) due to different soil salinity, soil moisture, and soil density. This suggests that the mineral composition, particle arrangement, and soil particle distributions might affect the electrical resistivity that causes the difference between in-situ and laboratory test. Laboratory test showed that there is a decrease of peat resistivity as soil moisture (form a curvilinear relationship with R^2 =0.1205) and soil salinity (form a nonlinear relationship with R^2 =0.8468) increase. However, the soil density (form a linear relationship with R^2 =0.9475) increases as the resistivity of peat increases. Furthermore, the shear strength of peat decreases and remained constant at a certain point as soil moisture and soil salinity increase; however, the shear strength of peat increased as soil density increased. The highly decomposed peat resulted in a lower peat resistivity, but, when compression, pressure, and compaction are applied on the peat, it will result in a higher peat resistivity.

The study revealed that the resistivity and shear strength of peat represent the same result as it increased as soil density increased and decreased as soil moisture and soil salinity increased. The electrical conductivity of peat when increased in soil moisture and soil salinity was higher than electrical conductivity of peat when increased in soil density. The results showed that by increasing the peat density might cause a higher electrical resistivity and shear strength and lower electrical conductivity in comparison to when increasing the peat salinity and soil moisture resulted in lower shear strength and electrical resistivity and higher electrical conductivity. The degree of peat humification would be an important factor in electrical resistivity and shear strength efficiency and a good understanding for colloidal of peat highlighted the reasons for its behaviour. Furthermore, the results for in-situ field test showed that the resistivity of peat for Line 1 (with R^2 =0.6306) and Line 2 (with R^2 =0.4852) was higher compared to Line 3 (with R^2 =0.9319), Line 4 (with R^2 =0.9398), Line 5 (with R^2 =0.9784), and Line 6 (with R^2 =0.9863) because both Line 1 and Line 2 have lower value for soil salinity and soil moisture. However, Line 2 showed that the area was influenced by more organic materials compared to Line 1 and Line 3. In conclusion, Line 2 showed most stable and the firmest soil foundation, since it has the highest soil resistivity data and soil shear strength data. Even though the soil moisture and soil salinity for Line 2 were lower than Line 3, the presence of organic material that the empty void and spaces in the soil medium making it more compacted and firmed foundation. Hence, the Wenner four-point probe method might be able to determine the soil resistivity with ease, but it might not be able to explain the situation between Line 1 and Line 2 without correlating it with the vane shear method. In conclusion, the vane shear test can assist in solving the situation the Wenner method could not explain. It can be implied from this study that the peat of the study area can be categorized as texture (soft loamy soil) and it is suitable for agriculture instead of construction. The relationship established between Wenner four-point probes and vane shear method can contribute to ground engineering design and would enhance the site suitability investigation. Future work on DUALEM-421 technique should be emphasised for better subsurface exploration accuracy and resolve peat depth for an in-situ test.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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