Geotechnical Synthesis of 2D-Electrical Resistivity Tomography of Geomaterial – Laboratory Model Study

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ABSTRACT

In this paper, a laboratory scale model study was conducted on interbeded geomaterial using electrical resistivity instrument. The electrical resistivity value of individual material was determined and modeled as mass scale. The tank was filled with composite geomaterial constituted of interbedding of cement mortar as hard layer and residual sedimentary soil. Forty-one copper electrodes of 15 cm long were used and installed at 4 cm spacing in the tank. The composite geomaterials were labeled as Model 1, Model 2 and Model 3, where they were referred respectively to interbedding of hard layer and layers of residual soil at natural dry state and wet state. The electrical resistivity terrameter was used to obtain the georesistivity pseudo-section by adopting Werner protocol. The georesistivity pseudo-sections were derived from 3 models simulated the subsurface of rock mass in humid tropic environment. The objective was to synthesize the composite georesistivity pseudo-section based on geo-engineering principle. It was observed that the pseudo-section of the composite geomaterial was represented by range of colors with range of georesistivity values. The horizontal bands of color differentiated the georesistivity of models vertically but constant in horizontal direction. The georesistivity value at material scale was comparable to the range of georesistivity values derived from the 2D electrical resistivity pseudo-sections. The contrasts in the conductivity of clay fraction, silica and electrolytes have differentiated the electrical resistivity pseudo-section of sandy soil mass and cement mortar hard material.

Keywords: *Electrical resistivity tomography, georesistivity, pseudo-section, residual soil*

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INTRODUCTION

The electrical resistivity survey is one of the geophysical techniques widely used for decades by developed countries for subsurface exploration such as groundwater exploration, groundwater pollution monitoring, mineral prospecting, general geology and geotechnical mapping[1], [2], [3]. The advantages are due to the non destructive and environmental friendly technique and cost effective for very large or difficult sites. Despite the substandard practice of conventional site exploration, this technology is not popular in Malaysia's construction industry. The geotechnical subsurface investigation by electrical resistivity survey challenges the competency to synthesize the 2D electrical resistivity pseudo-section subsequently determine the true subsurface properties and their correlation to engineering parameters. The electrical resistivity pseudo-section is an artificial image of the georesistivity of the medium derives from electrical resistivity survey. Soil and rock are made up of minerals and the electrical conduction of the masses depends on mineral types, presence of moisture, density, porosity and other distinct anomaly. Many studies have successfully established the electrical resistivity index of soil and rock, however the pseudo-section analysis is usually further verify by borehole logging [4], [5].

The laboratory study modeled typical interbeded sedimentary rock mass in humid tropic environment. The objective is to evaluate the reliability of electrical resistivity survey in subsurface exploration by synthesizing the electrical resistivity pseudo-section from the man-made models. Each pseudo-section is derived from known physical properties of cement mortar and residual soil modeled at three different environments. The logical interpretation of electrical resistivity image is vital and must be inline with geotechnical engineering principle in order to promote its applications.

MATERIAL AND METHOD

Two types of material were used, cement mortar, representing hard material, and tropical weathered sedimentary residual soil. The hard material was made from Portland cement, 0.05 mm diameter silica sand and standard tap water, all of which mixed at a ratio of 1:3:0.5. The mixture was then dried at room temperature of 3 ^{o}C. While the particle size classification test was conducted on residual soil in accordance to BS 1377: Part 1 1990 [6] and the residual soil mineral was determined by an X-ray Diffractometer test.

A petrography study was conducted to determine the micro texture of the hard material. The electrical resisitivity index of residual soil and cement mortar were determined by running an electrical resistivity test on the representative sample using a multimeter. The test was repeated on the residual soil samples of 2.0 g/cm^3 bulk density, 19 % bulk porosity and ranges of moisture content. Then the georesistivity value of the wet soil sample was recorded for 7 days by observing the changes in the georesistivity value as the samples were left to dry at room temperature. However, no such procedure was essential for cement mortar since it was assumed that homogenous man made is hard material with bulk density of 2.0 g/cm^3 and bulk porosity of 26 %.

Then a model tank was fabricated (183 cm long, 39 cm wide, and 100 cm high) braced with steel. It was made having 3 sides of timber plank and one side clear perspex. The composite geomaterial models were laid horizontally, which was an interbedding of cement mortar overlaid by residual soil. Forty-one copper electrodes with length of 15 cm were installed in a single line at 4 cm spacing onto the material surface. The soil moisture probe was earlier embedded into the composite for recording the moisture content at the point of reading the electrical resistivity value using ABEM Terrameter [7]. The soil moisture probe was 1-meter length with a pair of sensor rings at the lower and upper ends to detect the soil and hard layer moisture content around its radius. Doing so, the effect of wetting and natural drying up of the composite to the resistivity pseudo section could be read and this study named the electrical resistivity of the geomaterial ‘georesistivity’.

Then the composite geomaterial models were labeled Model 1, Model 2, and Model 3. Model 1 and Model 2 were referred to as hard layer overlaid by two layers of residual soil, at natural dry state and wet state respectively. While Model 3 was an extension of Model 2, capped by a hard layer. Every layer of geomaterial was compacted uniformly to form a homogenous composite. The hard and residual soil layers’ bulk density and bulk porosity were made of the same as material scale. The thickness of each material layer was determined by the ratio of length of array to thickness of image recommended by the manual. The Wenner array was selected as it gave strong signal, regardless of background noises in the working area [5]. The typical laboratory model set up is as shown in Figure 1.

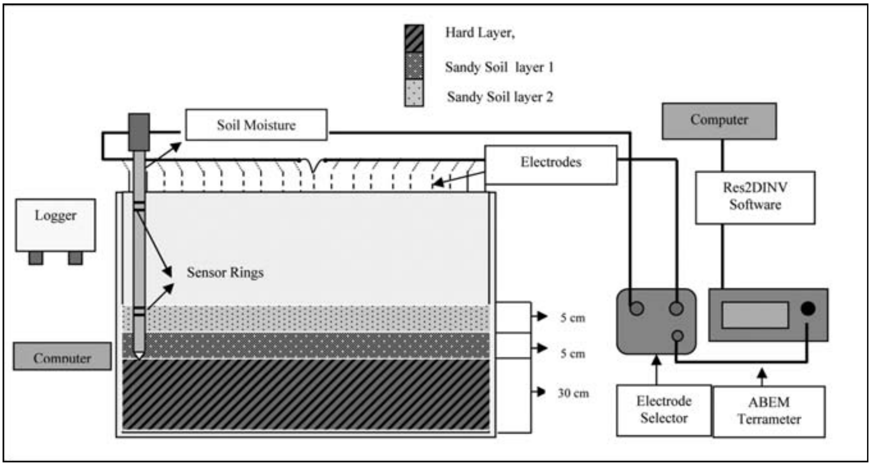

Figure 1: Schematic Layout of Model Tank with Interbeded Geomaterial

The default software provides a selection of electrode spacing [7]. The resistivity image was captured at selected spacing of 4 cm similar to the electrodes spacing installed in the tank. Subsequently, the total thickness of georesistivity pseudo section obtained was 74 cm. Then, the georesistivity pseudo-section thickness to the individual material thickness was calculated proportionately.

RESULTS AND DISCUSSION

Geomaterial Physical Properties

According to British Standard Classification System, the residual soil is classified as Well-graded Sand (SW) constitutes of gravel between 21 % to 34 %, sand particles ranging from 62 % to 77 %, and the percentage of fine is 0.3 % to 3.6 %. The fine is classified as soil particles size less than 0.002 mm. The coefficient of uniformity, C_u, is more than 6.0 and coefficient of gradation, C_g, is between 1 and 3. From the X-Ray Diffraction test, the fines fraction of sandy soil is made up of 220 count of clay minerals, 116 count of silicates, 41 count of phosphates, 10 count of borates mineral, 5 count of vanadates mineral, 7 count of nitride, 25 count of sulfide, 8 count of carbonates, 4 count of oxides mineral, and one count of arsenate mineral. The clay minerals composition is the highest, follows by silicates, phosphates and the rest. Clay mineral is known to absorb and sustain moisture comparatively to gravel and sand. In the present of moisture the clay minerals ionizes easily and contributes to the supply of free ions [8]. Inevitably has lower electrical resistivity value as compared to the rest of the minerals.

Figure 2 shows the cemented micro texture of the cement mortar made up of silica sand grains and calcite as filler. In the experiment, the monochrome color of the silica sand was black, grey and off-white due to the reflection and refraction of light on the particles. The sample bulk density was 2 g/cm^3 and bulk porosity of 26 %. Comparatively, the 0.05 mm silica mineral had higher resistance than calcite and much greater than clay mineral.

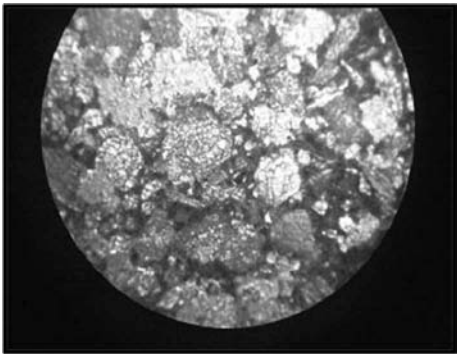

Figure 2: Micro Texture of Cemented Cement Mortar

Georesistivity of Cement Mortar and Sandy Soil Samples

The results of georesistivity value for 10 samples of cement mortar at wet and oven-dried conditions were measured using multimeter and are summarize in Table 1.0. The samples were soaked for 7 days. After Day 1, the moisture content for 10 samples varied from 7.13 % to 8.68 % and the georesistivity value recorded was from 82.66 Ωm to 122.78 Ωm with a mean value of 100.81 Ωm. As the soaking increased to 2 days, 5 days and ultimately 7 days, the georesistivity range of value decreased accordingly (see Table 1). The percentage decreased in the georesistivity value was 27.8% from Day 1 to Day 2 with increased moisture content of only 0.09%. In total, the georesistivity value of the cement mortar soaked from Day 1 to Day 7 reduced considerably from the highest value of 122.78 Ωm to the lowest 36.55 Ωm, which was a reduction of 54%. The total increase in the moisture content was 0.14%, which was barely significant.

Subsequently, after Day 7, the soaked samples were oven-dried in the next 7 days and the georesistivity reading was recorded. On Day 1, the georesistivity value was from 726.70 Ωm to 1,091.24 Ωm with a mean value of 900.09 Ωm. After Day 2, the georesistivity value decreased to a mean value of 766.83 Ωm, Day 5 the mean value was 263.46 Ωm and Day 7 171.65 Ωm. In total the georesistivity value decreased by 81%. A graphical plot of georesistivity value of cement mortar at wetting and drying states are shown in Figure 3. The trend line of wetted and oven-dried cement mortar is non-linear and non-parallel profile. In the experiment, the slight presence of moisture in the sample produced positive reading of material resistivity. However as the moisture content increased the electrical resistivity of the cement mortar reduced (see Table 1). The increase in the moisture content (electrolytes) within the pores reduced the resistivity value of the bulk cement mortar. At this juncture, the effect was not caused by the changes in the physical property of the cement mortar, but due to electrolytes conduction through the material. The oven dried process had accelerated the rate of moisture reduction, hence the resistivity values dropped drastically after 2 days, signifying the georesistivity value dependence on the amount of moisture in the pores of the hard material.

Similar test was conducted on 16 representative samples of sandy soil. The behavior of soil resistivity properties to the moisture content was plotted by log-normal scale, as in Figure 4. At initial moisture content of 26.67 %, the georesistivity of well graded sandy soil was 34.98 Ωm . The moisture reduced gradually to 21.65% at the end of a period of 7 days. Ultimately, the soil georesistivity value increased to 375.71 Ωm with an average value of 235.81 Ωm. At the lowest moisture content of 13.6 %, the highest georesistivity value was 1,007.90 Ωm. A strong polynomial relationship trend was observed but no optimum moisture content could be determined explicitly.

In this case, the well graded sandy soil with fraction of clay had propensity to adsorb and sustained moisture comparable to coarse-grained, hard cement mortar. At the same bulk density, the bulk porosity of cement mortar was higher than well graded sandy soil. Thus the tendency of the bulk georesistivity value to overlap between well graded sandy soils and cement mortar is very likely in the presence of moisture as electrolytes.

Table 1: Summary of Georesistivity Value of Cement Mortar with Respect to Moisture Content

Wetting	Georesistivity (Ωm) Range (mean)	Moisture Content (%) Range (mean)
	Wet Sample	
Day 1	82.66 - 122.78 (100.81)	7.13 - 8.68 (7.90)
Day 2	59.89 - 88.04 (72.83)	7.24 - 8.74 (7.99)
Day 5	49.59 - 76.21 (61.38)	7.24 - 8.78 (8.01)
Day 7	36.55 - 54.15 (46.36)	7.23 - 8.85 (8.04)
Drying	Oven-dried Sample	
Day 1	726.70-1,091.24 (900.09)	n.a
Day 2	583.98-927.10 (766.83)	n.a
Day 5	183.73-316.68 (263.46)	n.a
Day 7	137.07-208.95 (171.65)	n.a

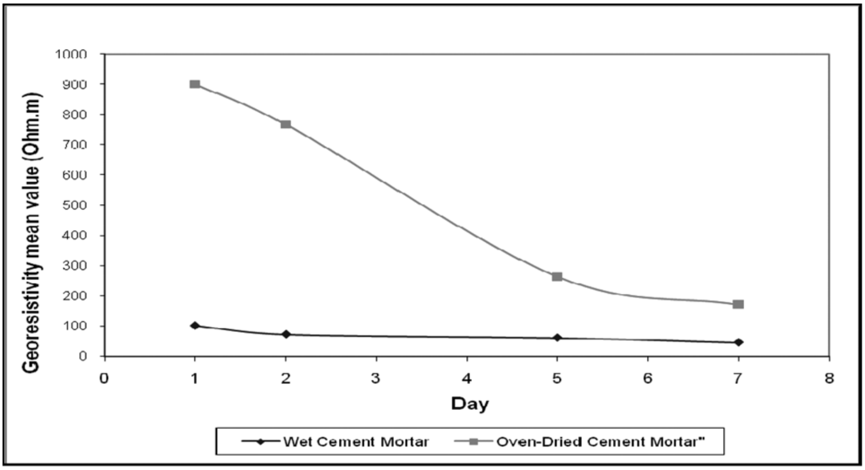

Figure 3: Georesistivity Mean Value of Cement Mortar at Wetting and Drying State

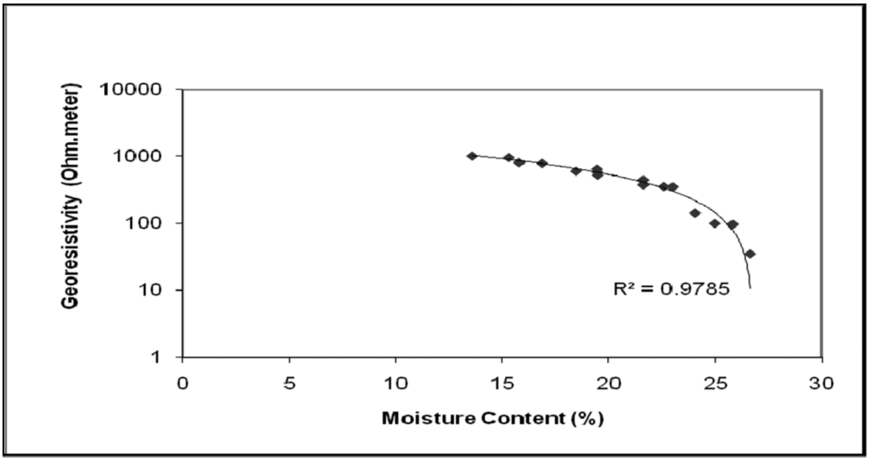

Figure 4: Georesistivity Mean Value versus Moisture Content of Sandy Soil Sample

Georesistivity Behavior of Interbeded Geomaterial

Model 1 – Dry condition

The electrical resistivity survey on Model 1 was conducted at dry condition. As a result, no signal output was detected by the 41 electrodes as both media apposed the flow of electric current. The failure of electrical conduction through the dry medium imposed limits on the effectiveness of the electrical resistivity survey for subsurface exploration in dry environment.

Model 2 – Undrained condition

The 2D georesistivity pseudo-section for Model 2 in wet and undrained condition is shown in Figure 5. The x-axis represents the length of image and the y-axis is the depth indicator of the root mean square error (RMS). While the electrode spacing and inverse model resistivity section is represented by color codes in unit of ohm.m. Figure 5 too shows the georesistivity pseudo-section at 0.5 % moisture by weight, where the total depth of pseudo-section is 74 mm for approximately 183 cm survey length. Seventeen color codes, each representing certain resistivity value, formed horizontal bands parallel to each other and aligned to the geomaterial bedding. Nevertheless there are sinking layer image at both ends indicating excessive compaction.

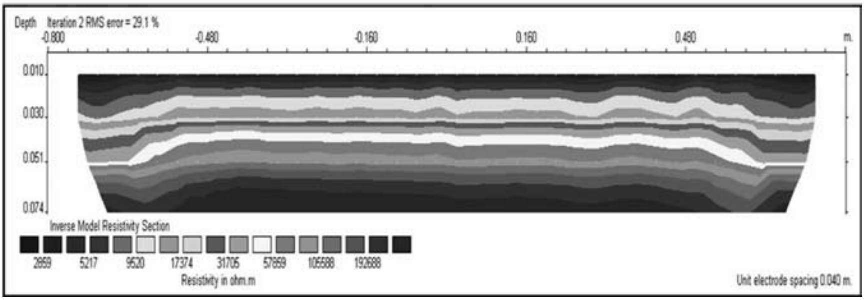

Figure 5: Georesistivity Images for Model 2 At 0.5% by Weight of Water

The RMS error for model 2 is 29.1 %, ideally the RMS error should be zero. Previous study recommended an acceptable background noise level is between 20 % to 30 % to recover the major geologic features [9]. The georesistivity pseudo-section is classified by bands of color where the georesistivity decreases with depth. The dotted lines illustrate the image boundary for sandy soil layer 1, sandy soil layer 2 and hard layer. The thickness ratio was found to be of 1:1:6. Table 2 tabulates the respective georesistivity values by color code and the material image thickness calculated is 9.3 mm for sandy soil layer 2 and soil layer 1 while hard layer is 55.4 mm thick. The sandy soil 2 at the top surface has georesistivity value less than 2859 Ωm, designated by dark blue. The sandy soil layer 1, underneath is slightly has slightly lower value of 2,859 to 5,217 Ωm, marked by blue and custom blue in spite of both layers have the same bulk density, but was compacted separately. The hard layer is marked by shades of green, yellow, orange, red, turquoise and violet, illustrates the range of georesistivity value between 5,217 Ωm. to 192,688 Ωm. Although the hard layer is made of cement mortar and assumed to be homogenous, the variation in the georesistivity color image may indicates the irregularity in the bulk porosity. Since the model was wetted by water poured from the top surface, therefore, obviously it can be expected that upper soil layer is wetter than lower layer. Similarly the upper surface of hard layer is wetter than the base, although the side walls at the bottom edge were made perforated to permit for water dissipation.

The changes in the pseudo-section elucidate the evidence of hydraulic permeability by gravity flow in vertical direction through the media in the form of differential horizontal color bands. A significant variation of georesistivity values are observed vertically but are uniform horizontally.

Table 2: Georesistivity Pseudo-Section Analysis for Model 2 at 0.5% by Weight of Water

Geomaterial medium	Material Thickness (mm)	Cum. Image Thickness (mm)	Colour		Georesistivity (Ωm)
			Description	Code	
Soil Layer 2	50	9.3	Dark Blue		≤ 2,859
Soil Layer 1	50	10.0	Blue		2,859 – 5,217
		18.6	Custom Blue		
Hard Layer (Cement Mortar)	300	19	Light Blue		5,217 – 9,520
		25	Custom Light Blue		
		30	Turquoise		
		33	Custom Light Green		9,520 – 17,374
		38	Bright Green		
		44	Green		17,374 – 31,705
		47	Lime		
		49	Yellow		31,705 – 57,859
		51	Custom Light Brown		
		54	Orange		57,859 – 105,588
		58	Red		
		67	Custom Red		105,588 – 192,688
		72	Plum		
		74	Violet		

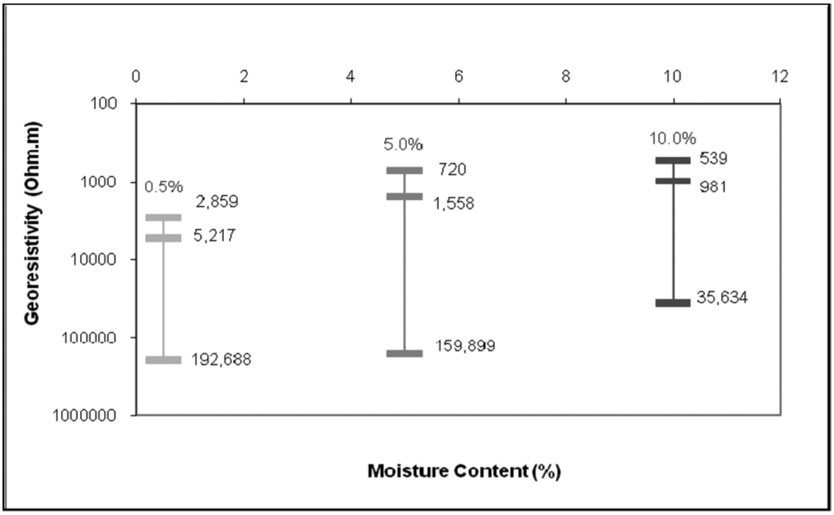

Figure 6: Georesistivity Values at 0.5%, 5%, and 10% by Weight of Water for Model 2

The georesistivity reading was repeated for 5 % and 10 % increased in weight of water and the successive results were analyzed. The result showed that the RMS error for 5 % and 10 % moisture were 19.8 % and 9.9 % respectively. The georesistivity pseudo-section analysis was plotted (Figure 6). The uniform georesistivity value for sandy soil and hard layer were observed and consistently decreased vertically with the increase of moisture content. At 5 % by weight of water, the sandy soils' georesistivity value decreased by 75 % and further reduced at 10 %. In total, the georesistivity value of sandy soil converged by 81 %. Similar trends occurred to the hard layer; however, the georesistivity value was relatively much higher than the sandy soil, justified by their respective bulk porosity. The upper and lower bound had the same amount of total reduction in georesistivity value with an average of 81 %. In summary, at the same geomaterial bulk density but dissimilar bulk porosity and mineralogy, the electrolytes leveraged the electrical resistivity pseudo-section.

Model 3 – Drained condition

Model 3 was designed to study the georesistivity pseudo-section of compressible soil under drained condition. The draining process of compressible sandy soil was expedited by making small holes on the 3 sides of the tank. The model was first allowed to dry at room temperature with air circulation and later topped up with surcharge load onto hard layer 2. It was assumed that the hard layers at the top and bottom were incompressible, thus confining the 3 layers of compressible sandy soil in the middle. Under a surcharge load, the overburden pressure compacted the soil and excreted the moisture via the holes. The electrical resistivity readings were taken at an interval of 7 days. The typical electrical resistivity pseudo-section is shown in Figure 7.

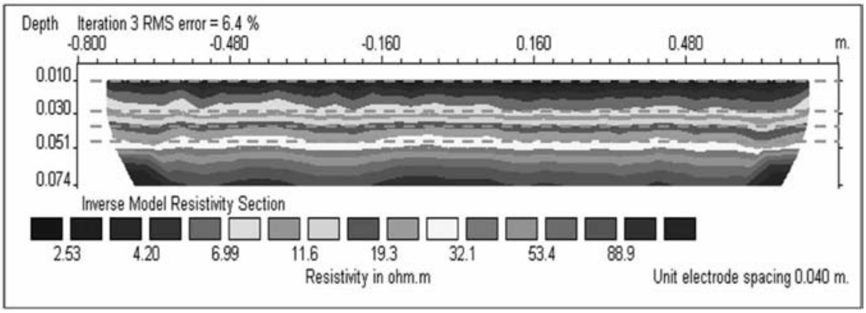

Figure 7: Georesistivity Pseudo-Section of Model 3 at Drained Condition without Surcharge

When measured, the total thickness of Model 3 was 850 mm. With the same survey layout, the total depth of electrical resistivity pseudo-section was also 74 mm. The electrical resistivity reading for each pseudo-section at different state is summarized as in Table 3.

On Day 7, without surcharge, the bulk moisture content was more of less constant but the bulk georesistivity value of soil increased slightly with depth. In circulated air at room temperature, the moisture decreased a little and the bulk georesistivity value increased concurrently. The georesistivity of soil layer 1 was then higher than the soil layer 3 on Day 28. It was observed that with the addition of 0.7 kN/m surcharge load, the bulk georesistivity value for soil layer decreased significantly by variation of 10 Ωm to 33 Ωm. As the reading was taken immediately, this happened could be due to the effect of moisture saturation within the soil masses. Similar behavior of georesistivity tomogram was observed although the surcharge load increased substantially where the moisture reduced by less than 0.3 % and the georesistivity increased about just 1 %. Over time, on Day 70, the georesistivity value began to increase as the dissipation of moisture took place.

Table 3: Georesistivity Pseudo-Section Analysis for Model 3 at Drained Condition

	Georesistivity (Ohm.m) , moisture content (%)							
Cum. Duration	7 days	14 days	21 days	28 days	35 days	42 days	49 days	70 days
Surcharge	0	0	0	0	0.7 kN/m	1 kN/m	2 kN/m	2 kN/m
Hard layer2	< 3.93	< 4.65	< 5.13	< 5.43	na	na	na	na
	24.37%	23.71%	23.22%	22.86%	na	na	na	na
Soil layer 3	6.75 – 20.0	8.02 – 23.9	8.89 – 26.7	9.43 – 28.5	10 - 17.3	10.3 – 17.7	11.4 – 19.1	14.6-24.1
	20.78%	20.65%	20.57%	19.98%	19.92%	19.80%	19.62%	17.25%
Soil layer 2	20.0 – 34.3	23.9 – 41.2	26.7 – 46.3	28.5 – 49.4	17.3-30.1	17.7 – 30.6	19.1 – 31.7	24.1-39.9
	20.78%	20.65%	20.57%	19.98%	19.92%	19.80%	19.62%	17.25%
Soil layer 1	34.3 – 59.0	41.2 – 71.1	46.3 – 80.2	49.4 – 85.8	30.1-52.2	30.6-52.6	31.7-52.8	39.9-66.0
	20.78%	20.65%	20.57%	19.98%	19.92%	19.80%	19.80%	17.25%
Hard layer1	59.0-174	71.1-212	80.2 - 241	85.8-259	na	na	na	na

Engineering properties of both residual soil and rock (cement mortar) materials are significantly different by physical properties, hardness and strength, with and without moisture content. The residual soil mass is the decomposition and disintegration of parent rock, naturally the density, porosity, mineralogy and the micro-structure are dissimilar. On the contrary, electrical resistivity survey technique reads the microstructure characteristics of the medium in the form of their electrical conduction priority and presence of electrolytes. Unless there is a contrast in the electrical conduction of the subsurface, the determination of homogeneity of soil mass, rock mass and the abnormality of subsurface is a very challenging task to describe precisely.

CONCLUSION

This experimental study had shown the georesistivity behavior of well graded sandy soil and hard material (rock) simulated humid tropic environment. The engineering properties of both materials were defined and made constant with obvious strength and hardness. The georesistivity value at material scale was found comparable to the range of georesistivity values which were derived from the 2D electrical resistivity pseudo-section, at range of moisture content. Meanwhile, the disparities in the conductivity of clay fraction, silica and electrolytes had differentiated the electrical resistivity pseudo-section of sandy soil mass and cement mortar hard material.

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