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The Influence of Basic Physical Properties of Soil on its Electrical Resistivity Value under Loose and Dense Condition

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Abstract. Electrical resistivity technique has become a famous alternative tool in subsurface characterization. In the past, several interpretations of electrical resistivity results were unable to be delivered in a strong justification due to lack of appreciation of soil mechanics. Traditionally, interpreters will come out with different conclusion which commonly from qualitative point of view thus creating some uncertainty regarding the result reliability. Most engineers desire to apply any techniques in their project which are able to provide some clear justification with strong, reliable and meaningful results. In order to reduce the problem, this study presents the influence of basic physical properties of soil due to the electrical resistivity value under loose and dense condition. Two different conditions of soil embankment model were tested under electrical resistivity test and basic geotechnical test. It was found that the electrical resistivity value (ERV, ρ) was highly influenced by the variations of soil basic physical properties (BPP) with particular reference to moisture content (w), densities ($\rho_{bulk/dry}$), void ratio (e), porosity (η) and particle grain fraction (d) of soil. Strong relationship between ERV and BPP can be clearly presents such as $\rho \propto 1/w$, $\rho \propto 1/\rho_{bulk/dry}$, $\rho \propto e$ and $\rho \propto \eta$. This study therefore contributes a means of ERV data interpretation using BPP in order to reduce ambiguity of ERV result and interpretation discussed among related persons such as geophysicist, engineers and geologist who applied these electrical resistivity techniques in subsurface profile assessment.

1. Introduction

Electrical resistivity technique (ERT) was a sub method from geophysical method. Geophysical method was a field that applied a principle of physics to study an earth. This field was originally championed by people from geophysicist that has a strong background and fundamental of physical sciences. Some of the physics properties used were electrical resistance, seismic velocity, density, magnetic susceptibility, etc. Recent continuous rapid development of technology has produced sophisticated innovative geophysical equipment such as electrical resistivity, seismic methods, gravity, ground penetrating radar, magnetic, etc. However, the standard performance of individual geophysical method were still depends on fundamental physical constraints, e.g. penetration, resolution, and signal to-noise ratio [1]. Traditionally, most of the data measured from field will be analyzed using utility software with an anomaly contrast. Finally, this anomaly contrast will be interpreted subjectively based on past references and expert experience. In the past, ERT has widely adopted in engineering, environmental and archeological studies. Commonly, the main objective of ERT application was for the detection and as a mapping tools for bedrock and overburden materials [2], groundwater [3] – [5], contamination plumes [6] and [7] meteorite crater [8], etc. ERT has increasingly popular in geotechnical and structural engineering works due to its good efficiency in terms of cost (lower cost), time (less time) and provides large data coverage (2D image) which is therefore able to complement the existing borehole data [9] – [13]. Conventional geotechnical drilling test can only determine information at particular drilling (1D information) point thus require soil interpolation which may be wide in contrast against ERT which can possibly provide a continuous image of the subsurface profile [14]. Field operations require less manpower while data processing and results have become quite easy and fast to be produced compared to the conventional drilling method. ERT consist of several separated set of devices and equipment is suitable to be used as an alternative tool for subsurface site investigation especially in situations of difficult accessibility for the application of conventional borehole method. Furthermore, ERT adopts surface techniques which require minimal contact to the ground thus reducing site damageability during the field measurement [15].

Ground exploration was always associated with subsurface profile characterization which relative to soil and rock characteristics. It is important to have a comprehensive site assessment which importantly used as a design input for construction of civil engineering structure. In engineering perspective, soil has being defined as material that can be worked without drilling or blasting [16]. Basically, soil consists of three natural intermixture of materials which is solid, water and air. Generally, soil can be divided into two major groups which is coarse and fine soil. Coarse soil consists of gravel and sand while fine soil consists of silt and clay particles fraction. Each type of soil has a unique characteristics derived from its nature of uncertainties. However, quantification of basic physical properties of soil may helps engineers to understand their fundamental and mechanics.

The operational process of ERM involving field measurement, data processing, interpretation and conclusion was always championed by physicists due to it being within their field of expertise. Hence, previous ongoing problem regarding the application of ERM gave rise to some lack of confidence among the engineers who were often bemused by the lack of clarity of results and justification produced by geophysicist. There is too much unclear information being covered up by geophysicists especially when they are dealing with geophysical methods related to geotechnical works. According to [15], geophysicists still possess only little appreciation from an engineer’s point of view and lack the knowledge of the soil science. Furthermore as reported by [9], some geophysical results and conclusions are difficult to assimilate in sound and definitive ways as some geophysicists attempt to hide their expertise for business reasons. In the past, conventional geophysicist interpretation practice was too obsessed with qualitative anomaly approach which sometimes creates some unconvincing justification and weak results verification. Furthermore, conventional reference tables of geomaterials used for anomaly interpretation also sometimes was difficult to decipher due to its wide range of variation and overlapping values [17]. As a result, a strong verification is vital to support the interpretation outcome which otherwise have been traditionally interpreted based on a qualitative approach depending on the experience of the expert [18]. Otherwise, ERM interpretation will always be subjected to doubts arising from uncertainties and unreliability. Moreover, too many geophysical methods have been used without any reference to the geological situation thus producing disappointed results that lead to a mistrust of the geophysical method by many engineers [15].

As a result, the solutions to these challenges will require multidisciplinary research across the social and physical sciences and engineering [19]. The success at any site investigation works is based on the integration of method [20]. According to [13], studies that relate to geophysical data and geotechnical properties are much rarer and lesser known. Hence, this study proposed the influence of basic physical properties of soil (soil moisture content, densities, specific gravity, void ratio and porosity supported by grain size characteristics) with electrical resistivity value using small scale trial embankment with soil fill placed in a loose and dense condition in order to reduce some black box and ambiguities of electrical resistivity anomaly interpretation via quantitative integration analysis between electrical resistivity value and geotechnical properties. As reported by [14], the quantification of geotechnical properties has become an important factor for rigorous application of resistivity technique in engineering applications.

2. Methodology

This study was performed via fieldwork, laboratory work and data processing. Fieldwork was begun with constructing a small soil embankment model using lateritic soil in loose condition. Dimensions of soil model were 3.0 (length, m) x 1.0 (wide, m) x 0.3048 (height, m) with all sides of the model edge shaped into a gentle slope < 45°. Then, a line of electrical resistivity test was performed using a single leveled line of 2D tomography imaging on the top of each soil model based on electrode configurations using ABEM SAS 4000 equipment as shown in Table 1. Two land resistivity cables were connected to 41 steel electrodes via jumper cables. Then, both resistivity land cables were connected to the electrode selector and Terramater SAS 4000 data logger for field setup. Finally, 12 volt battery was connected to the data logger to supply direct current (DC) during the data acquisition. This study used Wenner array due to its simplicity and for good near surface data. As reported by [21], [22], Wenner array was applicable to obtain a dense near surface cover of resistivity data. Several considerations involving device and equipment setting, position of electrical resistivity line, ground condition, raw data processing etc. needed to be carefully considered and performed in order to determine the best ERV outcome. For example in order to reduce boundary effect that may reduced the ERV accuracy caused by refracted and reflected current, the electrical resistivity line was placed at the center of the soil model with additional offset (0.5m) from each end of its length. Based on [23], electrical current may propagate in geomaterials via the process of electrolysis where the current is carried by ions at a comparatively slow rate. Hence, soil models were poured with water before the electrical resistivity test was conducted. Otherwise, current will be loathed to propagate through the model due to the dry soil condition which will cause some error in the electrical resistivity readings. All raw data obtained from field measurement was transferred to the computer using SAS4000 utilities software. Then, those data was processed and analyzed using RES2DINV software of [24] to provide an inverse model that approximate the actual subsurface structure.

After that, field density test was performed on the top and center of the model using sand replacement method. Then, soil sample based on field density test was immediately taken to the geotechnical laboratory for density record, moisture content test (oven drying method), specific gravity test (gas jar method) and sieve test (wet and dry sieve). Dry and wet sieve test was performed (lateritic soil) due to its mixture of composition between coarse and fine grain of particles. Dry sieve test was conducted using mechanical shaker while hydrometer test was used for wet sieving. The entire related basic geotechnical test was based on [25]. Then, the soil model was compacted using a mechanical compacter and the whole testing process was repeated under dense condition. Both models under 2D Electrical resistivity data acquisition was given in Figure 1 while a schematic diagram representing soil sampling and electrical resistivity line alignment was given in Figure 2. As referred to in [25] and [16], the following equation (1-4 and 5-6) were used to calculate moisture content (w), bulk density (ρ_{bulk}), dry density (ρ_{dry}), specific gravity (Gs), void ratio (e) and porosity (η) of soil sample studied.

$$w = ((m_2 - m_3)/(m_3 - m_1)) \times 100 \quad (1)$$

where m_1 is the mass of container, m_2 is the mass of container and wet soil and m_3 is the mass of container and dry soil

$$\rho = (m_w/m_b)) \times \rho_a \quad (2)$$

where m_w is the mass of the wet soil from hole, m_b is mass of sand in hole and ρ_a is bulk density of sand

$$\rho_d = (100\rho)/(100 + w) \quad (3)$$

where ρ is the bulk density of soil and w is moisture content

$$G_s = (m_2 - m_1)/((m_4 - m_1) - (m_3 - m_2)) \quad (4)$$

where m_1 *i*s the mass of empty jar, m_2 is mass of bottle + dry soil, m_3 is mass of bottle + soil + water and m_4 is mass of bottle + water only

$$e = (G_s\rho_w/\rho_d) - 1 \quad (5)$$

where Gs is the specific gravity of soil, ρ_w is density of water and ρ_d is dry density of soil

$$n = (e/1 + e) \quad (6)$$

where e is the void ratio of soil

Table 1. Configuration used in 2D electrical resistivity test.

No	**Setting**	**Description**
1	Array	Wenner
2	Electrode specification	Small steel electrodes: 6 inch of length with 2 mm of diameter
3	Electrode spacing	0.05 m (50 mm)
4	Total number of electrode	41
5	Total number of small jumper cable	42
6	Total length of 2D resistivity test	2 m (2000 mm)

Figure 1. Soil model (lateritic soil) tested by 2D electrical resistivity test: Loose condition (left) and dense condition (right).

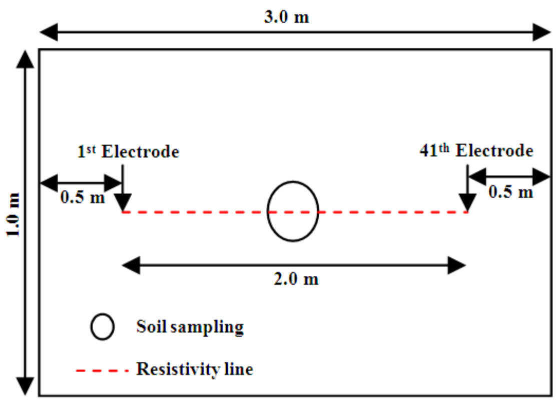

Figure 2. Schematic diagram of the soil sampling position and resistivity line alignment (drawing not to scale).

Figure 3. Field density test (left) and specific gravity test (right).

Figure 4. Mechanical sieve (left) and hydrometer test (right).

3. Results and Discussions

All results presented and discussed are based on field electrical resistivity value (ERV), basic physical properties of soil and relationship of field ERV with moisture content (*w*), density (ρ), void ratio (e), porosity (η) and grain size of soil (d). All results are presented in Figure 5 – 7 and Table 2.

3.1. Electrical resistivity value (ERV)

ERV was determined by measuring the potential difference at points on the ground surface which caused the propagation of direct current through the subsurface [26]. The ERV obtained in Table 2 was originally extracted from the global 2D electrical resistivity tomography section particularly at point L and D given in Figure 5 and 6. Each point of ERV was extracted at the exact location (horizontal: x and depth: y) of the soil sample tested. It was found that soil model under loose condition has higher ERV ($\rho_{(L)}$ = 48763 Ωm) compared to the dense soil model ($\rho_{(D)}$ = 1112 Ωm) due to the different composition of basic physical properties of soil such as solid, water and air. Electrical propagation in soil is largely electrolytic process by flowing in connected pore spaces and along grain boundaries of geomaterial [27].

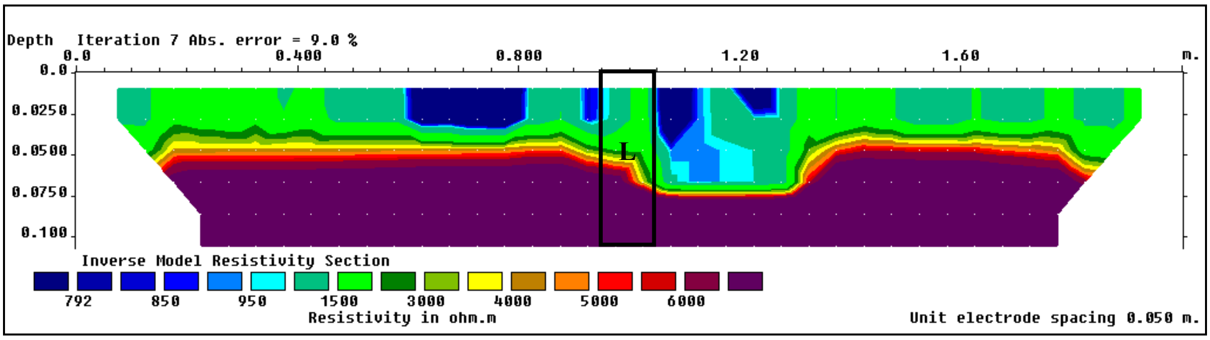

Figure 5. Global 2D electrical resistivity tomography section and localize selected point of ERV under loose condition (L).

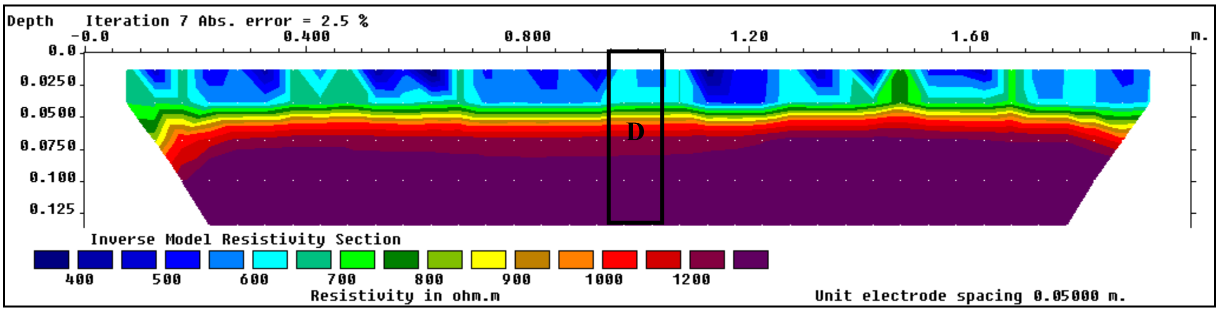

Figure 6. Global 2D electrical resistivity tomography section and localize selected point of ERV under dense condition (D).

3.2. Soil moisture content, void ratio, porosity, densities and grain size fraction

Basic physical properties of soil obtain from geotechnical analysis was given in Figure 7 and Table 2. At soil model under dense condition, it was found that the moisture content (*w*) value was higher compared to the loose soil model due to the random wetting process of soil model performed before the electrical resistivity data acquisition. Generally, both soil models have demonstrate a different variation of moisture content due to the dissimilarity of grain sizes present at both soil models. Even both of the soil model was built from the same lateritic soil, the variation of different particle fraction was still dissimilar due to the uncertainties nature of soil.

Specific gravity (Gs) test of each soil was conducted using 50 ml bottle. Each soil model was tested three times for averaging purposes. By knowing the Gs, void ratio and porosity of each soil model can be determined using mathematical equation as given in previous section. It was found that the lowest void ratio (e) and porosity (η) occurred at dense soil model (e = 0.4289 & η = 0.3002) compared to other loose soils soil model (e = 1.8210 & η = 0.6455). The variation of void ratio and porosity between dense and loose condition quite obvious due to the different quantity of basic physical properties of soil. These results may indicate that the soil have experienced a different degree of denseness derived from loose and dense state of model condition which can be observed and verified through the soil density results. Physically, the lower void ratio and porosity can indicate the soil was in dense condition and vice versa. The quantity of air and water in soil will be reduced due to the compaction process compared to the loose state condition. A relationship between void ratio and porosity was linear and this parameter has a big influence to the soil density variations.

In soil mechanics and geotechnical engineering, soil density was basically described using bulk density (ρ_{bulk}) and dry density (ρ_{dry}). Bulk density was defined by total mass of solids and water per total volume while dry density was defined by mass of solids per total volume. Quantities of densities provide a measure of the material quantity related to the space amount it occupies [16]. Dense soil model was found to higher density value (ρ_{bulk} = 2.034 Mg/m^3 & ρ_{dry} = 1.673 Mg/m^3) compared to the loose soil model (ρ_{bulk} = 1.289 Mg/m^3 & ρ_{dry} = 0.867 Mg/m^3) due to the geomaterials and moisture content variations. It can be observed that the densities of each soil model were relative to the moisture content variations by showing general relationship of densities was linearly proportional with the moisture content. Higher quantity of water will increased the total soil weight thus increasing its density and vice versa. Quantity of fine particles from dense soil model was also greater than loose soil model which allow more water to be absorb in order to increase its densities. Based on Table 2, quantity of clay and silt particles at dense soil model was greater than loose soil model. Loose soil model has a lower capability to absorb water due to its highly porous characteristics which consequently producing low soil densities. Hence, it was strongly believed that the grain size variation has also played some great influences to both soil model densities. Hence, it was strongly believed that the density of lateritic soil was linearly proportional to the presence of moisture content and fine gain geomaterial.

Generally, soil can be in the form of both granular and fine particle. Based on Figure 7 and Table 2, it was found that the lateritic soil was classified as Silty SAND (mixture of both granular and fine particle) based on engineering soil classification. All sieve analysis results of soil specimen tested from both models has shown some slightly variation in terms of grain size quantification due to the natural heterogeneity features of soil. Detailed results obtain in Table 2 was originally extracted from particle size distribution curve (PSD) presented in Figure 7.

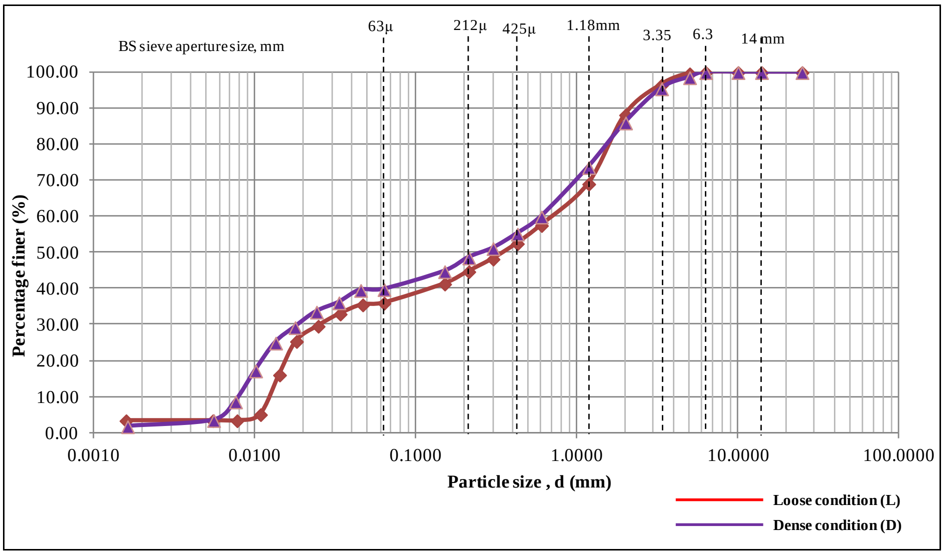

Figure 7. PSD curve for lateritic soil model at loose and dense condition.

Table 2. Extracted ERV and basic physical properties of soil model under loose and dense condition.

Soil Sample	Loose				Dense			
Electrical resistivity value, ρ (Ωm)	48763				1112			
Moisture content, *w* (%)	15.83				21.57			
Particle size analysis, d (μm – mm, %)	Clay	Silt	Sand	Gravel	Clay	Silt	Sand	Gravel
	3.38	32.62	52.23	11.77	1.72	38.05	46.24	13.99
	36.00		64.00		39.77		60.23	
Specific gravity, Gs	2.446				2.391			
Void ratio, e	1.8210				0.4289			
Porosity, η	0.6455				0.3002			
Bulk density, ρ_{bulk} (Mg/m^3)	1.289				2.034			
Dry density, ρ_{dry} (Mg/m^3)	0.867				1.673			

3.3. Relationship of Electrical Resistivity Value due to the basic physical properties of soil

All results from ERV and BPP were analyzed and presented using statistical bar chart in order to demonstrate some relationship between those properties investigated. Resistivity value was highly influenced by pore fluid and grain matrix of geomaterials [28]. As reported by [29], a soil's ERV generally varies inversely proportional to the water content and dissolved ion concentration as clayey soil exhibit high dissolved ion concentration, wet clayey soils have lowest resistivity of all soil materials while coarse, dry sand and gravel deposits and massive bedded and hard bedrocks have the highest ERV. Furthermore a decrease of ERV was results from an increased of metal ions or inorganic elements in geomaterials [30]. According to [31], soil parameters determined in grain size analysis could replicate the variety of resistivities obtained on the site very well. Hence, the field ERV can give varying values due to the variation of soil physical state. In other words, BPP can strongly influence the field ERV due to soil composition variation such as relative to the quantity of solid, air and water.

Based on Figure 8 and 9, it was found that the ERV was high due to the lower moisture content and vice versa. As illustrated in Figure 8, the highest ERV from loose soil model ($\rho_{(L)}$ = 48763 Ωm) was highly influenced by the least amount of moisture content ($w_{(L)}$ = 15.83 %). In contrast, the highest amount of moisture content ($w_{(D)}$ = 21.57 %) has influenced dense soil model ($\rho_{(D)}$ = 1112 Ωm) for having the lowest field ERV. As stated by [23], electrical current may propagate in geomaterials via the process of electrolysis where the current was carried by ions at a comparatively slow rate. The application of field ERT has theoretically stated that the water content in subsurface materials has a close positive correlation with the electrical conductivity [32]. Hence, it was shown that ERV obtained from both soil model was highly influenced by the presence of moisture content which can be established by a general relationship that the field ERV was inversely proportional to the amount of moisture content ($\rho \propto 1/w$) since a higher moisture content will caused field ERV to be low and vice versa.

This controlled miniature model study also revealed that the soil electrical resistivity value was highly influenced by the presence of air void content. The ERV of soil model was found to be very high ($\rho_{(L)}$ = 48763 Ωm) due to the high volume of void ($v_{(L)}$ = 1.821) and porosity ($\eta_{(L)}$ = 0.6455) based on the first soil model results which focused on loose trial embankment model. After that, the results from dense soil model has revealed that the ERV was reduced ($\rho_{(D)}$ = 1112 Ωm) together with the reduction of void ratio ($v_{(D)}$ = 1.821) and porosity ($\eta_{(D)}$ = 0.6455). Due to the loose condition of soil model, it enables a higher air filled void which able to increased the ERV over the range of the previous reference charts and tables. As reported by [33], air filled void posses a higher resistivity value compared with the water filled void. Hence, careful considerations such as supported data from others need to be considered in order to interpret a reliable result from loose soil condition. Otherwise, it can be wrongly interpreted as hard rock materials.

Based on Figure 8 and 9, it was found that soil densities under dense condition (ρ_{bulk} = 2.034 Mg/m^3 and ρ_{dry} = 1.673 Mg/m^3) has the lowest ERV ($\rho_{(D)}$ = 1112 Ωm) compared to the densities of soil model under loose condition (ρ_{bulk} = 1.289 Mg/m^3, ρ_{dry} = 1.867 Mg/m^3 and $\rho_{(L)}$ = 48763 Ωm). The soil density value of dense condition was higher than loose condition since the soil quantity of compact condition require more than loose condition. During the compaction effort, volume of air contained in pore was decreased and thus require an additional soil added and compacted until it fully fit according to the soil model dimension required. Hence, the amount of soil used was higher compared to the loose conditions which contribute to a greater value of densities. Under loose condition, soil consist higher of voids which dominantly filled by air thus contribute to a lower weight which relative to the lower densities value measured. In the past, void ratio and porosity can influence the variation of soil density since a denser soil was derived from the soils with a low void ratio and porosity and vice versa. This study has demonstrated that the denser soil will decreased the ERV due to the low void ratio and porosity. The low void ratio and porosity in dense soil will assist the current propagation (electrolysis process was easily due to low porosity which contained more water) thus producing a low ERV. Hence, this study has successfully demonstrated that the highest field ERV was due to the low soil densities which associate to higher volume of void and porosity as the relationship can be established as $\rho \propto 1/\rho_{bulk/dry}$.

According to [34], ERV can be influenced by soil grain size as a higher ERV was derived from the larger coarse soil and vice versa. Based on Figure 8 and 9, the highest field ERV was at loose soil model ($\rho_{(L)}$ = 48763 Ωm) which having the greatest amount of coarse soil (CS = 64.00 %) and lowest fine soil (FS = 36.00 %). In contrast, the lowest field ERV was at dense soil model ($\rho_{(D)}$ = 1112 Ωm) which composed of the lowest coarse soil (CS = 60.23 %) and highest fine soil (FS: 39.77 %). Hence, it was shown that the field ERV was influenced by the presence of soil grain size which can be stated by a general relationship that the ERV was linearly proportional to the amount coarse soil (ρ α CS) since the higher ERV was caused by the higher amount of coarse soil. In other case, a lower ERV also has demonstrates a significant relationship due to the higher composition of fine soil. Hence, the relationship of field ERV due to the fine soil can be established as ρ α 1/FS. Furthermore, the higher quantity of fine soil will allow more water to be absorbed thus helps the ease of current propagation and finally will reduced the ERV.

However in some cases, those general relationships presented will turn inversely especially when the properties obtained was almost similar to each other. Hence, other major non similar properties will take placed to influence the field ERV. Based on [35], detailed study related to the field condition such as porosity, degree of saturation, salt concentration in pore fluid, grain size, size gradation, temperature and activity can produce more accurate correlation performed from the laboratory experiment. Hence, it has been shown that the ERV was influenced by the BPP variations. This study can contribute to the related parties which used the electrical resistivity technique (ERT) as a strong verification of ERV interpretation. Conventional subjective anomaly interpretation of ERV can possibly being enhanced using the BPP relationship thus increasing the sense of appreciation and confidence level of an engineers to applied ERT in geotechnical site investigation (GSI). Moreover, the ERV reliability can also being increased objectively due to the strong direct data verification (BPP). According to [15], geophysical techniques offer the chance to overcome some of the problems inherent in the more conventional ground investigation techniques. Hence, further research can possibly be studied in the future such as the application of ERT as a tool to predict the BGP quantitatively. Current GSI works is growing rapidly thus require an alternative tool such as ERT in order to assist and enhanced the conventional GSI techniques (drilling method). Based on [9], it is important to quantify the BGP numerically for the purpose of analysis and design. Furthermore, BGP can further influence the geotechnical engineering properties such as shear strength and compressibility. ERT can benefit our sustainable ground investigation since it can reduce time, money and compliment others conventional method especially by its surface (non-destructive) 2D/3D surface technique of investigation.

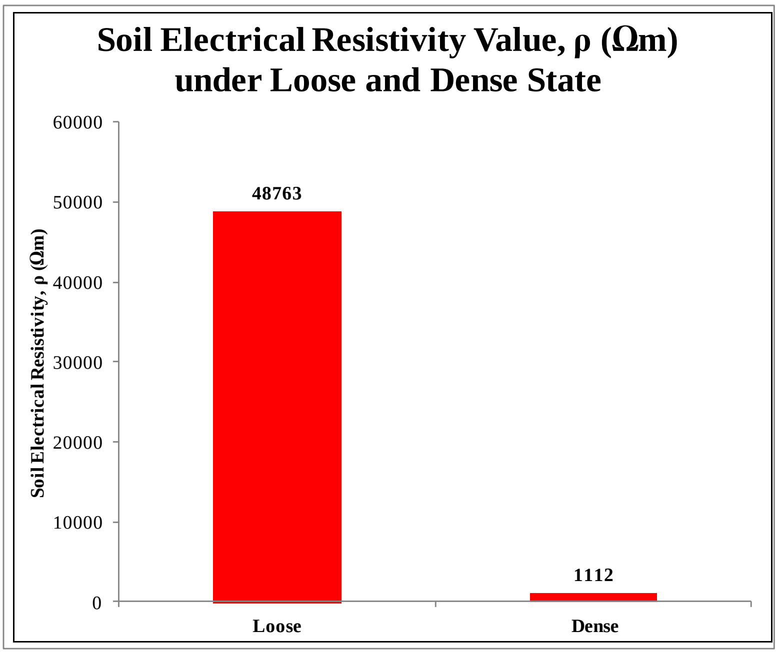

Figure 8. ERV of soil model under loose and dense condition.

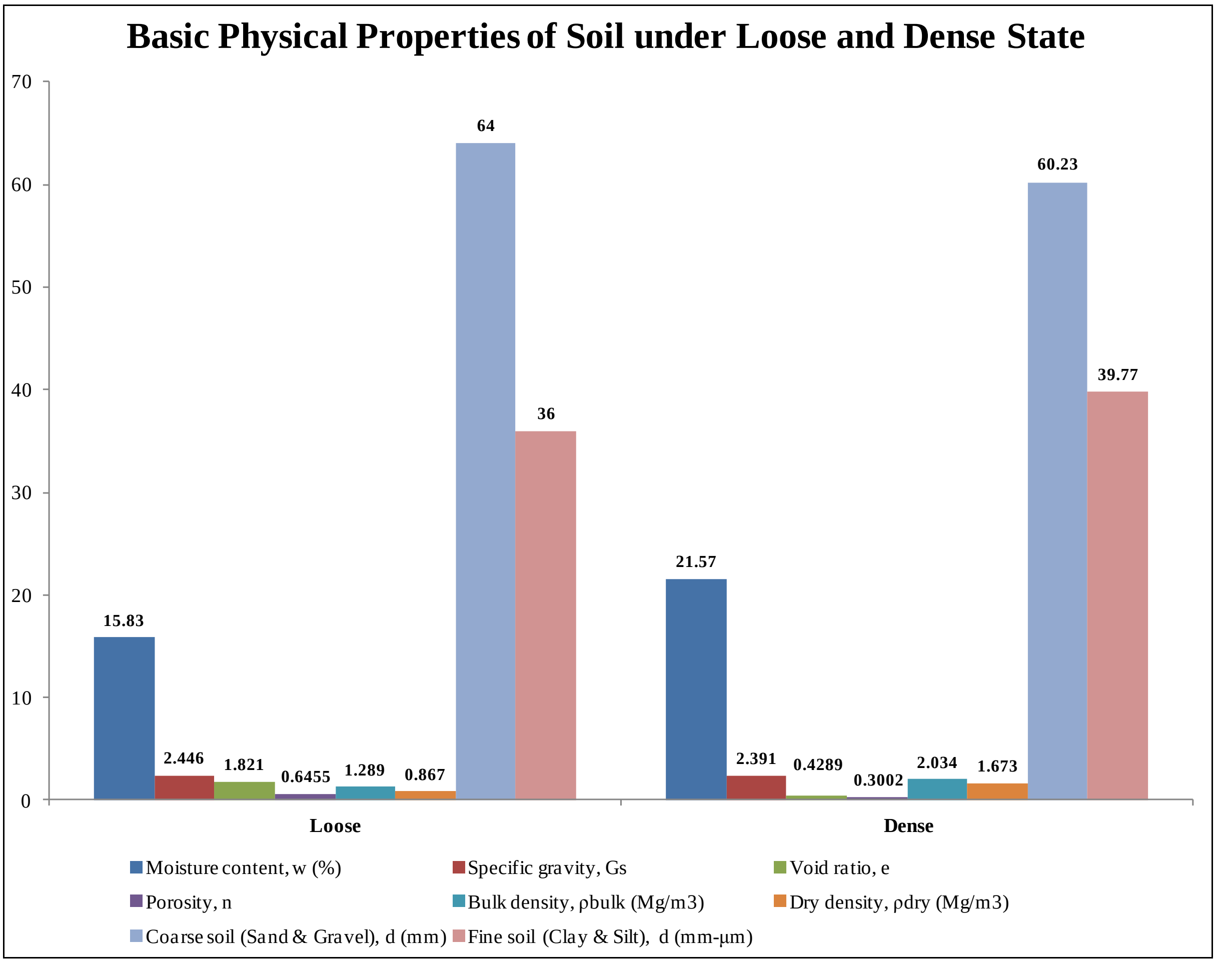

Figure 9. Basic physical properties of soil model under loose and dense condition.

4. Conclusion

The electrical resistivity value of Silty SAND was successfully performed under loose and dense state of small soil embankment model. The influence on soil resistivity value due to variations of moisture content, densities, void ratio, porosity and grain size fraction was successfully and methodically studies and presented. The ERV was influenced by the variation of soil physical state which related to the composition of water, air and solid in soil such as its sensitivity to the quantitative proportion of water, porosity and geomaterial particle fractions under different denseness condition. Different denseness level of soil has creates some variations to the basic physical properties of soil such as the dense condition has less void and porosity compared to the loose condition. The integration of geophysical results such as electrical resistivity value with basic physical properties of soil obtained from geotechnical testing and formulation provided a meaningful contribution to the geophysicist and geotechnical engineers since it applicable to minimize and explain some of the ambiguity during the data interpretation stage. Hence, the confidences level and reliability of electrical resistivity results can be increased due to the strong verification and supporting data obtained from the laboratory test.

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