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General Relationship between Field Electrical Resistivity Value (ERV) and Basic Geotechnical Properties (BGP)

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Abstract: Electrical resistivity technique is a popular alternative method used in geotechnical soil investigations. Most past applications have been particularly in the area of subsurface ground investigations such as to locate boulder, bedrock, water table, etc. Traditionally, this method was performed by a geophysicist expert for data acquisition, processing and interpretation. The final outcome from the electrical resistivity technique was an anomaly image which used to describe and conclude the particular soil condition measured. The anomalies highlighted uncertainties on the nature of soil that was often variable and depended on each particular site condition that gave a site dependent soil electrical resistivity value (ERV). Hence, this study demonstrates a relationship between ERV (ρ) and some of the basic geotechnical properties (BGP) such as soil moisture content (w), grain size of geomaterial (CS or FS), density (ρ_{bulk} and ρ_{dry}), porosity (η), void ratio (e) and Atterberg limit (AL). Different soil samples were collected and tested under field and laboratory conditions to determine basic geotechnical properties immediately after the field electrical resistivity method was performed. It was found that the electrical resistivity value was different for number of soils tested and was relatively subjective to variations in the geotechnical properties. In other words, electrical resistivity value was greatly influenced by the geotechnical properties as the ERV was higher due to the lower moisture content, void ratio and porosity with a higher value of soil density and vice versa. The relationship of ERV and BGP can be described by ρ α 1/w, ρ α CS, ρ α 1/FS, ρ α $\rho_{bulk/dry}$ and ρ α 1/AL. Hence, it was shown that behaviour of ERV was significantly influenced by the variation of basic soil properties and thus applicable to support and enhance the conventional stand alone anomaly outcome which is traditionally used for interpretation purposes.

Keywords: Soil Investigation, Anomaly, Electrical Resistivity Value, Basic Geotechnical Properties

1. Introduction

Geophysical techniques consist of electrical resistivity, seismic, gravity, ground penetrating radar, electromagnetic, etc. Basically, a geophysical technique used to study an earth based on physics properties obtained during the data acquisition stage. Several physical properties that have been measured from geophysical techniques were resistivity, velocity, density, magnetic susceptibility, etc. As reported by Khatri et al. [1], conventional SI such as drilling methods experiences difficulties in steep and hilly terrain, swampy areas, coastal regions and complex geomaterial areas which need to be investigated. Hence, electrical resistivity technique (ERT) has been increasingly used in ground investigation due to its ability to be performed in difficult site conditions. Generally, the whole process of ERT involving data acquisition, field raw data processing using utilities software and finally come out with an anomaly interpretation.

Conventionally, interpretations of investigations obtained with geophysical techniques such as ERT are controlled by physicists and geologists with considerable expertise in their respective fields, but posses less ideas of construction constraints within construction interest and civil engineering necessity [2]. This common practice creates problems to engineers since the deductions made by the geophysicist are difficult to accept mainly due to the weak and changing justification which solely relative to the interpreter experienced. Without strong verification, the ERT poses some unconvincing conclusion due to several reasons. The existing geomaterials references obtained from published tables and charts are used for ERV anomaly interpretation. These were difficult to choose due to its wide range of

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variation and overlapping values. Geoelectrical resistivity value used to characterize subsurface profile material is necessarily subjected to local ground condition and the characterization occurs within overlapping classifications [3]. Furthermore, different description and conclusion can possibly arise with a different interpreter for the same particular anomaly outcome. In current geotechnical activity, engineer desires strong verification from the geophysicist since the ERT is performed indirectly as a surface measurement in order to justify the subsurface anomaly. This problem commonly occurs since the ERT is controlled by a person who has little knowledge and appreciation of soil mechanics. For example, geophysicists still possess little appreciation to the engineer's point of view and lack the knowledge of the mechanics of soils [2]. According to Fraiha and Silva [4] and Benson et al. [5], geophysical methods are insufficient to stand alone in order to provide solutions to any particular problems.

Studies relating geophysical data with geotechnical properties are rare and less known [6]. Geotechnical property quantification was an important factor for geophysical methods used in engineering applications [7]. Those black boxes have led this study to investigate the relationship of geophysical properties (ERV) with other related properties with particular reference to basic geotechnical properties (BGP) such as moisture content, density, porosity, void ratio, etc. This study capable to contribute as a strong verification input to the field ERV in order to describe and conclude their anomaly image in much convincing and meaningful interpretation.

2. 2D Resistivity Imaging and Laboratory Testing

This study performed both field resistivity imaging (2D) and geotechnical laboratory testing. A single line of 2D resistivity survey was conducted at Universiti Sains Malaysia using ABEM SAS (4000) set of equipment as shown in Fig. 1. Field resistivity measurements were conducted using mini electrodes (150 mm long with 2-3 mm diameter) with 17 cm electrode spacing. Total of 42 mini electrodes were used during the survey: 41 electrodes are for 2 resistivity land cable connected by jumper cables and a single electrode for remote current electrode. Then, two resistivity land cables and a single remote cable were connected to the Terrameter SAS (4000) data logger and electrode selector during data acquisition. Resistivity line was performed using pole dipole array due to its dense and deeper penetration data. Finally, the 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 [8] to provide an inverse model that approximate the actual subsurface structure. Then, three disturbed soil samples were taken to the laboratory for classification tests. The soil samples were taken from the same location as the resistivity line at three different points as shown in Fig. 2. Soil samples were obtained within the depths of 0-24 cm. Geotechnical tests used in this study were particle size distribution (dry and wet sieve), specific gravity, field density (sand replacement method), Atterberg limit and moisture content. As referred to in [9] and [10], the following Equations 1 to 5 and Equations 6 to 7 were used to calculate moisture content (w), bulk density (ρ), dry density (ρd), specific gravity (Gs) , plasticity index (Ip), void ratio (e) and porosity (n) of soil samples studied.

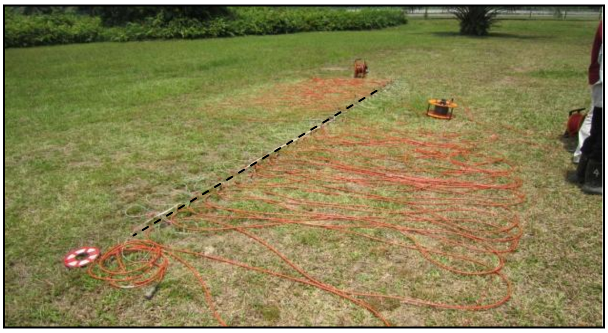

Fig. 1 2D resistivity data acquisition in progress.

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

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_b 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 is 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.

$$I_p = w_L - w_P \quad (5)$$

where w_L is the liquid limit, w_p is plastic limit.

$$e = (G_s\rho_w/\rho_d) - 1 \quad (6)$$

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

$$n = (e/1 + e) \quad (7)$$

where e is the void ratio of soil.

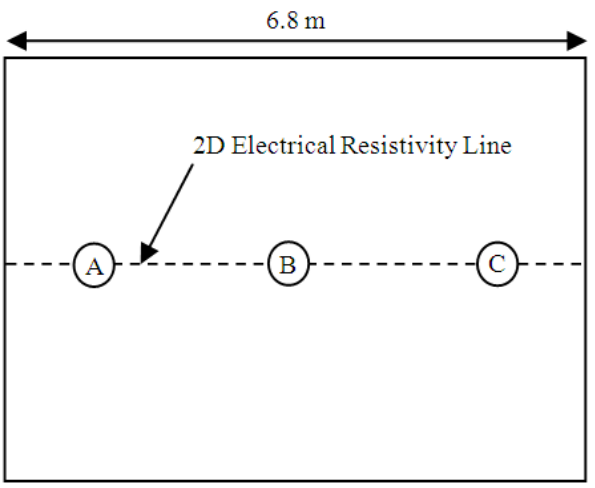

Fig. 2 Schematic diagram (Plan view) of the position of soil sampling and resistivity line alignment.

3. Results and Discussion

All results are presented and discussed based on field electrical resistivity value (ERV), basic geotechnical properties (BGP) and general relationship of field ERV with the BGP. All results are presented in Fig. 3 to Fig. 6, while the summary results of ERV and BGP can be referred in Table 1 (Appendix).

3.1 Field Electrical Resistivity Value (ERV)

ERV was determined, in accordance with [11] by measuring the potential difference at points on the Earth's surface which were produced consequent to the injection of direct current through the subsurface. Three (3) localized points of ERV (A, B and C) were extracted from a line of 2D subsurface profile section, as can be seen in Fig. 3, that produced using RES2DINV software. Each point of ERV was extracted from depth within 0-24 cm, and at the same location (horizontal: x and depth: y) as the soil sampling.

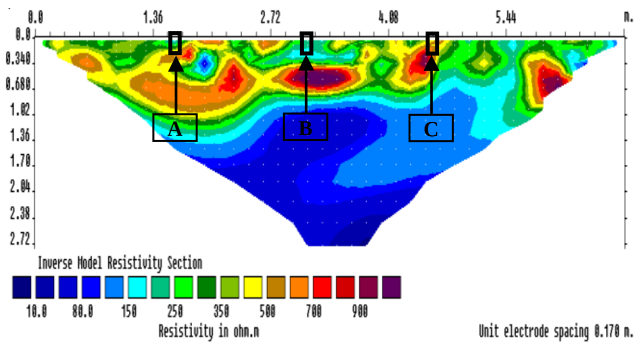

Fig. 3 2D electrical resistivity section and localize extracted ERV (A, B and C) used for further detail study.

This study used pole-dipole array since it is capable to produce dense resistivity data in order to produce detailed subsurface profiling. It was found that the highest ERV was at point A (434 Ωm) followed by point C (396 Ωm) and B (305 Ωm) respectively. Field ERV can be obtained inconsistently due to the influence of other factors especially that of geometry factor. Field ERV was determined based on an array used which is derived from different geometry factor. Different field ERV will be produced due to the different arrays used such as Wenner, Schlumberger, Dipole-dipole, Pole-dipole, Gradient, etc. It must be made clear that each array has its own advantages and disadvantages. The choice of array selection normally is based on the objectives of researcher/investigator (e.g: groundwater, overburden, bedrock, etc). For example, Wenner array is good in horizontal structure mapping but experiences low data while Pole-dipole is able to produce dense data and deeper depth of investigation.

3.2 Basic Geotechnical Properties (BGP)

Three (3) disturbed soil samples were collected and taken to the geotechnical laboratory for further investigations. Based on particle size distribution analysis test, it was found that all soils were Clayey SILT as shown in Fig. 4. The differences between those three soil samples was only based on differences in percentages of coarse and fine soil; soil A comprised of the highest coarse soil (C: 24.19%) and lowest fine soil (F: 75.81%) followed by soil C (C: 22.86% & F: 77.14%) and B (C: 20.51% & F: 79.49%) respectively.

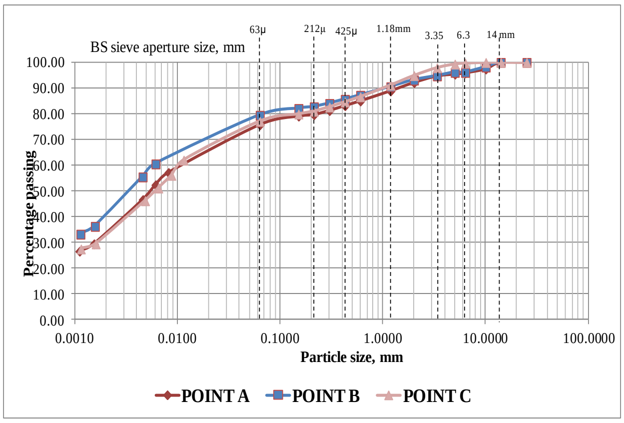

Fig. 4 PSD curve for soil sample at point A, B and C.

The Atterberg limit test was conducted to determine the soil consistency limits due to the high silt content detected from sieve analysis test. It was found that the liquid limit (LL) of soil B (53%) was the highest compared to others (A and C: 48%). Based on LL obtained, soil B was categorized as high plasticity MH while soil A and C was intermediate plasticity (MI). Based on plasticity index (PI) result obtained, it was found that all PI value of soil was less than 20% which confirmed that the soil was silt. Hence based on plasticity chart for the fine soils classification, it was categorized that soil B was a SILT of high plasticity (MH) while soil A and C was SILT of intermediate plasticity (MI).

Several factors can influence the variation of soil Atterberg limit result such as geomaterial size and shape. According to Whitlow [10], fine soil such as silts and clay are highly influenced on engineering properties by shape rather than size of particle. Fine soils such as clay and silts are usually flaky in shape. The variation of Atterberg limit may caused by the difference flaky shape mixed with other materials which caused the water changes for all soil tested thus having properties which are naturally varied.

In line with hydrometer test, specific gravity (G_S) test of each soil was conducted using 50 ml bottle. Each soil (A, B and C) was tested three times for averaging purposes. It was found that the G_S of soil A (2.10) was greater than G_S of soil C (2.03) and B (1.98) respectively. The G_S value was showing a small variation (0.12) due to the same type of soil (Clayey SILT). The G_S value obtained in this study was also showing a small value (1.98 – 2.03) due to the very shallow soil sampling which possibly influence by top soil materials such as organic matter (e.g. plant roots, etc). By knowing the G_S, void ratio and porosity of all soil 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 soil A (e: 0.246 and η: 0.198) compared to other soils at soil C (e: 0.316 and η: 0.240) and B (e: 0.313 and η: 0.238). The variation of void ratio and porosity between soil A with soil B and C was quite obvious compared to the small void ratio and porosity variation between soil B and C. These results may indicate that the soil have experienced a different degree of compaction 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. A relationship between void ratio and porosity was linear and this parameter has a big influence to the soil density variations.

Sand replacement method was performed to determine the field density (Bulk density: ρ_{bulk} and Dry density: ρ_{dry}) at point A-C. It was found that the value of density of point A (ρ_{bulk}: 1.692 Mg/m^3 and ρ_{dry}: 1.249 Mg/m^3) was greater than density value at point C (ρ_{bulk}: 1.551 Mg/m^3 and ρ_{dry}: 1.107 Mg/m^3) and B (ρ_{bulk}: 1.517 Mg/m^3 and ρ_{dry}: 1.020 Mg/m^3) respectively. The density value variation for all points was not significantly large due to the closed characteristics of soils (ρ_{bulk} variation: 0.175 Mg/m^3 while ρ_{dry} variation: 0.229 Mg/m^3). This density value variation was greatly influenced by the value of void ratio and porosity obtained previously. For example, the lower void ratio and porosity will caused the soil to be a dense soil (high density soil) such as soil A. Soil moisture content was also recorded during the sand replacement test. It was found that the highest moisture content was located at point B (48.68%) followed by point C (40.12%) and A (35.52%) respectively. The composition of soil at point B which has the highest quantity of fine soil can contribute to its highest moisture content compared to the others point. In contrast, the more coarse soil composition can contribute to the lower moisture content due to its ability to drain or evaporate water in rapid condition compared to the fine soil.

3.3 General Relationship of Field ERV and BGP

The results from field ERV and BGP were analyzed using statistical bar chart in order to demonstrate a general relationship of field ERV due to the BGP. According to Griffiths and King [12], resistivity value was highly influenced by pore fluid and grain matrix of geomaterials. Hence, the field ERV can give varying values due to the variation of soil physical state. In other words, BGP can strongly influence the field ERV due to soil composition variation such as relative to the quantity of solid, air and water.

Based on Fig. 5, it was found that the field ERV was high due to the lower moisture content and vice versa. The highest field ERV from soil A (434 Ωm) was highly influenced by the least amount of moisture content (35.52%). In contrast, the highest amount of moisture content (B: 48.68%) has influenced soil B (305 Ωm) for having the lowest field ERV. As stated by Telford et al. [13], 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 [14]. Hence, it was shown that field ERV was highly influenced by the presence of moisture content which can be established by a general relationship that the field ERT was inversely proportional to the amount of moisture content ($\rho \ \alpha \ 1/w$) since a higher moisture content will caused field ERV to be low and vice versa.

Chik and Islam [15] have reported that the ERV can be influenced by soil grain size as a higher ERV was derived from the larger coarse soil and vice versa. According to Fig. 6, the highest field ERV was at soil A (434 Ωm) which having the greatest amount of coarse soil (CS: 24.19%) and lowest fine soil (FS: 75.81%). In contrast, the lowest field ERV was at soil B (305 Ωm) which composed of the lowest coarse soil (CS: 20.51%) and highest fine soil (FS: 79.49%). 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 field ERT was linearly proportional to the amount coarse soil ($\rho \ \alpha$ CS) since the higher field ERV was caused by the higher amount of coarse soil. In other case, a lower field 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 $\rho \ \alpha \ 1/FS$.

Based on Fig. 5, it was found that soil A (ρ_{bulk}: 1.692 Mg/m^3 and ρ_{dry}: 1.249 Mg/m^3) was the densest (Bulk and Dry density) followed by soil C (ρ_{bulk}: 1.551 Mg/m^3 and ρ_{dry}: 1.107 Mg/m^3) and B (ρ_{bulk}: 1.517 Mg/m^3 and ρ_{dry}: 1.020 Mg/m^3) respectively. 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. Moreover, large amount of water will be filled in soil with a high amount of porosity thus producing low field ERV. In contrast, denser soil will increased the field ERV due to the low void ratio and porosity. The low void ratio and porosity in dense soil will impede the current propagation (electrolysis process was difficult due to low porosity which contained less water) thus producing a higher field ERV. Hence, this study has successfully demonstrated that the highest field ERV was due to the high soil density (Bulk and Dry density) as the relationship can be established as $\rho \, \alpha \, \rho_{bulk/dry}$.

Fig. 6 demonstrates some relationship of field ERV due to the Atterberg limit (AL). It was strongly believed that the AL can influence the field ERV since it relative to the soil consistency which varies from solid to liquid state. The variation of soil consistency was greatly influenced by the amount of water presence in soil. It was found that the field ERV was lowest at soil B (305 Ωm) in relations with the highest value of liquid limit (LL: 53.00%), plastic limit (PL: 33.20 and plasticity index (PI: 19.80%). Both soil A and C which has greater field ERV was showing a lower AL properties compared to the soil B. Hence, the general relationship of field ERV due to the Atterberg limit can be established as $\rho \, \alpha \, 1/AL$.

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 Rinaldi and Cuestas [16], 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 field ERV was influenced by the BGP variations. This study can contribute to the related parties which used the electrical resistivity technique (ERT) as a strong verification of field ERV interpretation. Conventional subjective anomaly interpretation of field ERV can possibly being enhanced using the BGP relationship thus increasing the sense of appreciation and confidence level of an engineers to applied ERT in geotechnical site investigation (GSI). Moreover, the field ERV reliability can also being increased objectively due to the strong direct data verification (BGP). According to [2], 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 Whitlow [10], 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.

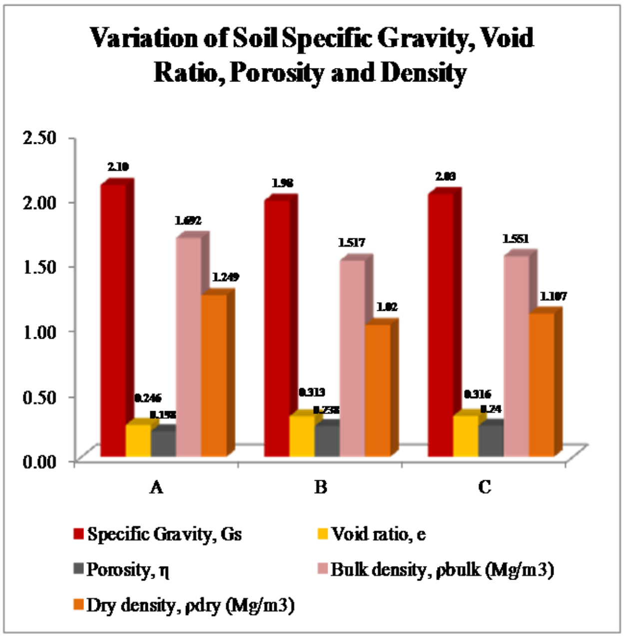

Fig. 5 Variations of BGP with particular reference to specific gravity, void ratio and porosity.

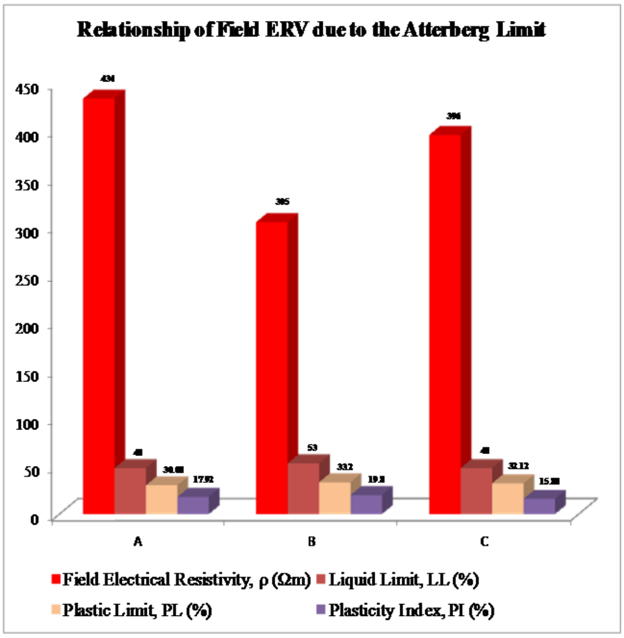

Fig. 6 Relationship of field ERV due to the moisture content and particle size of soil.

4. Conclusion

The relationship between ERV and BGP was successfully demonstrated specifically on Clayey SILT soil. All relationship shows that the BGP has influenced the ERV either in linear or inversely relationships. The field ERV was influenced by the variation of soil physical state which related to the composition of water, air and solid in soil. The establishment of BGP from geotechnical testing and formulation was strongly applicable to verify the field ERV in order to improve and increase the interpretation and reliability of field ERV.

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APPENDIX

Table 1. Summary results of ERV and BGP.

Soil Sample	A				B				C			
Field resistivity value, ρ (Ωm)	395				263				289			
Moisture content, m (%)	35.52				48.68				40.12			
Particle size analysis, d (μm – mm, %)	Clay	Silt	Sand	Gravel	Clay	Silt	Sand	Gravel	Clay	Silt	Sand	Gravel
	29.59	46.22	16.34	7.85	36.37	43.12	13.66	6.85	29.56	47.58	17.74	5.12
	75.81		24.19		79.49		20.51		77.14		22.86	
Specific gravity, Gs	2.10				1.98				2.03			
Void ratio, e	0.246				0.313				0.316			
Porosity, η	0.198				0.238				0.240			
Bulk density, ρ_{bulk} (Mg/m^3)	1.692				1.517				1.551			
Dry density, ρ_{dry} (Mg/m^3)	1.249				1.020				1.107			
Liquid limit, LL (%)	48.00				53.00				48.00			
Plastic limit, PL (%)	30.08				33.20				32.12			
Plasticity Index, PI (%)	17.92				19.80				15.88			