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CORRELATION ANALYSIS BETWEEN FIELD ELECTRICAL RESISTIVITY VALUE (ERV) AND BASIC GEOTECHNICAL PROPERTIES (BGP)

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Past applications of electrical resistivity surveying have particularly focused on areas of subsurface ground investigations to locate boulder, bedrock, water table, etc. Traditionally, electrical resistivity surveys were directed by an expert geophysicist for data acquisition, processing and interpretation. The final outcome from the electrical resistivity technique was an anomaly image that helped describe and demarcate zones of challenging ground conditions. The anomalies highlighted uncertain geotechnical conditions that were often irregular and dependent on individual site condition, yielding a site-dependent electrical resistivity value (ERV) for the ground. This study therefore identifies co-relationships between ERV and some basic geotechnical properties (BGP) such as soil moisture content, grain size of geomaterial, density, porosity, void ratio, and Atterberg limit. Different soil samples were collected and tested under both field and laboratory conditions. Basic geotechnical properties of the samples were obtained immediately after the electrical resistivity measurements were made. It was shown that the electrical resistivity value was greatly influenced by the geotechnical properties, and thus the resistivity surveying technique is applicable to support and enhance the conventional stand-alone anomaly outcome that is traditionally used in ground investigation interpretation.

1. Introduction

Geophysical techniques are used to study earthen materials based on their physical properties obtained during the data-acquisition stage. Such properties that have been so measured in geophysical techniques are resistivity, seismic velocity, density, magnetic susceptibility, etc. [1] have reported that the conventional ground investigation method of drilling experiences difficulties in steep and hilly terrain, swampy areas, coastal regions and in areas containing complex geo material. Hence, the electrical resistivity technique (ERT) has been increasingly used in ground investigation due to its ability to be used even in challenging site conditions. Generally, ERT is the whole process encompassing data acquisition and field raw data processing using reliably tested software and culminating in an anomaly interpretation.

Conventionally, interpretations of investigations obtained with geophysical techniques such as ERT are closely controlled by physicists and geologists having considerable expertise in their respective fields. However, such personnel often lack knowledge of construction constraints and construction and civil engineering requirements [2]. This common predicament creates problems to engineers since the

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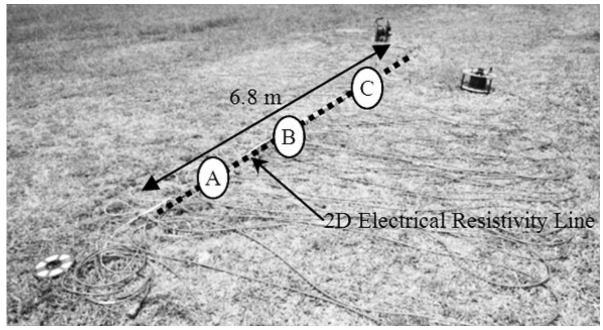

Fig. 1. 2D resistivity data line at field site and soil sampling locations.

deductions made by the geophysicist are often unacceptable due mainly to the weak and inconsistent justifications of the relatively inexperienced interpreter. Without strong verification, the ERT can pose some unconvincing conclusions due to several reasons. The existing geomaterial references obtained from published tables and charts are used for ERV anomaly interpretation. These are not easily adaptable due to its wide range of variation in the parametric values and the overlapping values. The electrical resistivity value used to characterize subsurface profile material is necessarily subjected to local ground conditions, and the characterization occurs within overlapping classifications [3]. Furthermore, different description and deductions can arise depending on the interpreter, even for the same singular anomaly outcome. In current geotechnical activity, the engineer desires strong verification from the geophysicist since the ERT is performed indirectly as a surface measurement in order to justify the subsurface anomaly. Geophysicists still possess only limited appreciation of the engineer's point of view and lack knowledge of the mechanics of soils. Geophysical methods are unable to stand alone in order to provide solutions to any particular problems [4, 5].

Studies relating geophysical data with geotechnical properties are rare and less known [6]. Geotechnical property quantification was an important expected outcome from geophysical methods used in engineering applications [7]. Such black boxes initiated this study to investigate the relationship of electrical resistivity 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 is a strong verification input to the ERV field in order to describe and form conclusion on their anomaly image through convincing and meaningful interpretation.

2. 2D Resistivity Imaging and Laboratory Testing

In this study we performed both field resistivity imaging (2D) and geotechnical laboratory testing. A single line of 2D resistivity survey was performed at Universiti Sains Malaysia using ABEM SAS (4,000) 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. A total of 42 mini-electrodes was used during the survey. Forty one electrodes were for two resistivity land cables connected by jumper cables, and a single electrode was used for the remote current electrode. Two resistivity land cables and a single remote cable were connected to the Terrameter SAS (4000) data logger with an electrode selector for comprehensive data acquisition. The pole dipole array was used in the resistivity line due to the need for 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 to provide an inverse model that approximates the actual subsurface structure [8]. In addition to the user friendliness of the software, RES2DINV is adopted worldwide as a resistivity data processing tool. Its use has been cited by many researchers involved in resistivity tomography studies [9-12]. The software is supplied by Geotomo

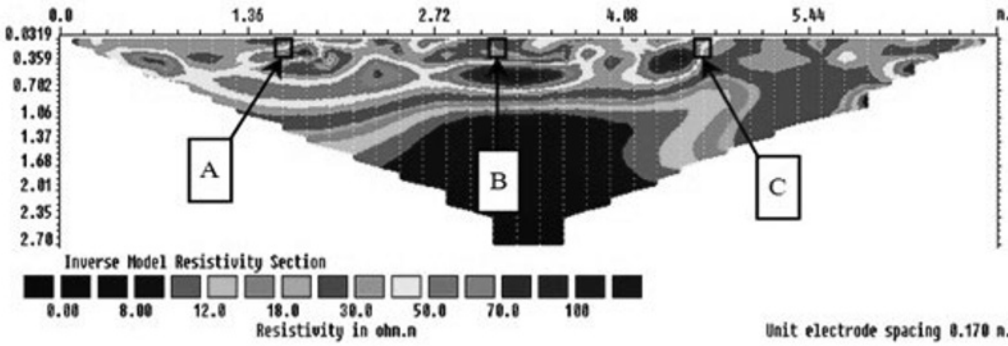

Fig. 2. 2D electrical resistivity section and localized extracted ERV (A, B, and C) used for further detailed study.

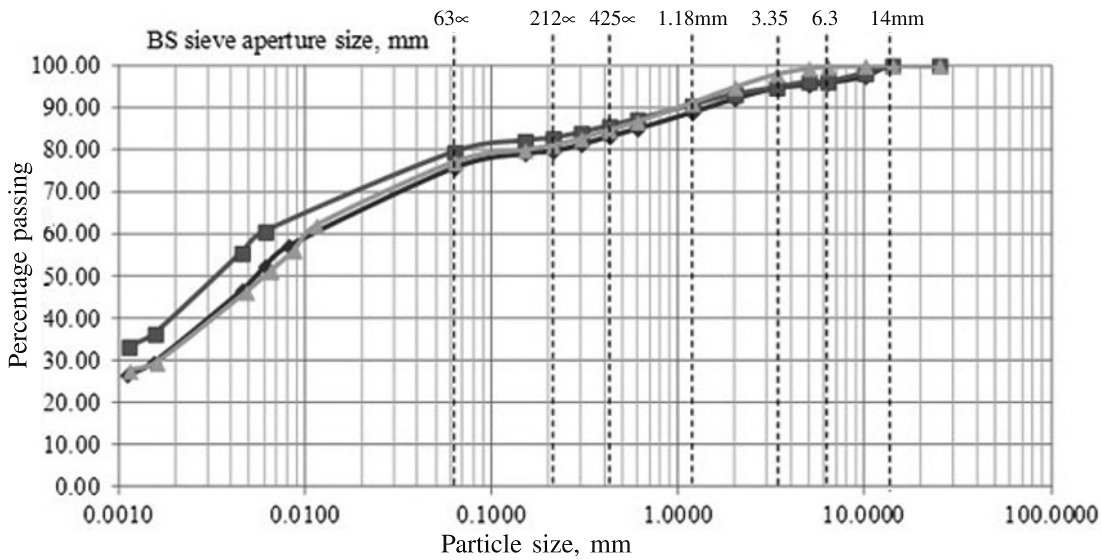

Fig. 3. PSD curve for soil samples collected from locations A, B, and C: −◆−) point A; −■−) point B; −▲−) point C.

Software Company in Penang, Malaysia. During the processing stage, the smooth constraint least square option was used in this particular study in order to produce a smooth boundary change, which was considered more suitable for representing the soil material in contrast to rock and fractured material which are more appropriately analyzed using the robust option due to the sharp changes in the geomaterial boundary. Three disturbed soil samples were taken to the laboratory for classification tests. The soil samples were taken from three different locations along the same resistivity line (see Fig. 1). Soil samples obtained were within the depths of 0-24 cm. Geotechnical tests used in this study concerned particle size distribution (dry and wet sieve), specific gravity, field density (sand replacement method), Atterberg limit, and moisture content. All tests were carried out in accordance with [13] and [14].

3. Results and Discussion

All results presented in Figs. 2-5 and Table 1 are based on the field electrical resistivity value (ERV), basic geotechnical properties (BGP), and general relationship of field ERV with the BGP.

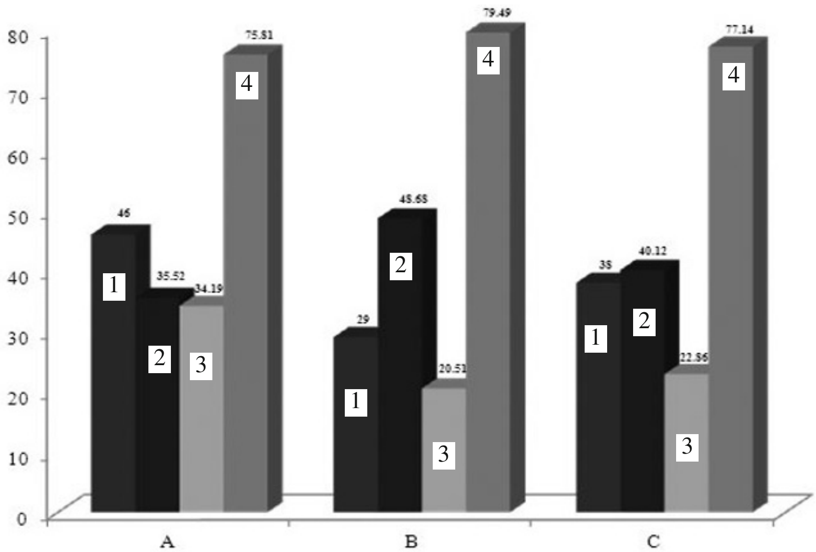

Fig. 4. Relationship of field ERV to the moisture content and particle size of soil: 1) field electrical resistivity ρ, Ωm; 2) moisture content *w*, %; 3) particle size (coarse soil) *d*, mm; 4) particle size (fine soil) *d*, mm-∝m.

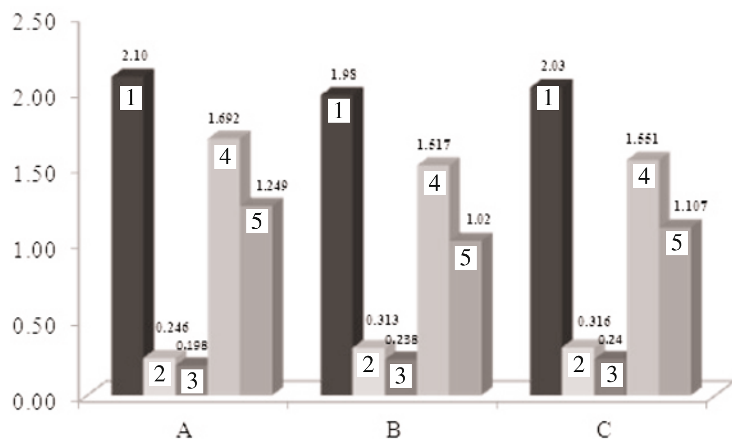

Fig. 5. Variations of BGP with particular reference to specific gravity, void ratio, porosity, and density: 1) specific gravity G_s; 2) void ratio *e*; 3) porosity η; 4) bulk density ρ_{bulk}, Mg/m^3; 5) dry density ρ_{dry}, Mg/m^3.

Table 1

Soil sample	A				B				C			
Field resistivity value ρ, Ωm	46				29				38			
Moisture content *w*, %	35.52				48.68				40.12			
Particle size analysis *d*, ∝m – 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 G_s	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			

3.1. Field Electrical Resistivity Value (ERV)

ERV was determined in accordance with [15] by measuring the potential difference across two points on the ground surface that is produced consequent to the injection of a direct current through the subsurface. The ERV at three localized points (A, B, and C) was obtained from a 2D subsurface profile section produced using RES2DINV software as presented in Fig. 3. ERV at these three locations was obtained from a depth within 0-24 cm, and soil sampling was done with surgical precision at the same geographic location (horizontal x and depth y). The pole-dipole array was used in this study in order to utilize its ability to produce dense resistivity data in order to produce a comprehensive subsurface profiling. The highest ERV was observed at point A (46 Ωm), followed by point C (38 Ωm) and B (29 Ωm). Based on [15, 16], the ERV value for silty soil is in the range 10-100 Ωm, and the soil sample collected indicated a high silt fraction as observed through the particle size distribution test (see Section 3.2). The field ERV obtained may be inconsistently due to the influence of other factors, especially that of geometry. Field ERV was determined based on the array used and depends significantly on the geometry of the array. According to [9, 17], different field ERV will be produced depending on the different arrays used (viz., Wenner, Schlumberger, dipole-dipole, pole-dipole, gradient, etc). It is clearly demonstrated that each array has its own advantages and disadvantages. Array selection is normally based on the objectives of the researcher (e.g., groundwater, overburden, bedrock, etc). For example, the Wenner array is good in horizontal structure mapping but provides low data, while pole-dipole is able to produce dense data and deeper depth of investigation.

3.2. Basic Geotechnical Properties (BGP)

Three disturbed soil samples were collected for further investigation and testing in the geotechnical laboratory. All soil samples are classed as Clayey silt, based on the results from the particle size distribution test and as shown in Fig. 3. However, the differences between these three soil samples was only in the differences in percentages of coarse and fine soil; soil A comprised the highest coarse soil (C − 24.19%) and lowest fine soil (F − 75.81%) followed by soil C (C − 22.86% and F − 77.14%) and B (C − 20.51% and F − 79.49%) respectively.

The Atterberg limit test was conducted in accordance with [13] to determine the soil consistency limits due to the high silt content detected from sieve analysis test. The plasticity index (PI) obtained for all the soil samples was less than 20%, which indicated that the soil was a silt. It was also observed that the liquid limit (LL) of soil B (53%) was the highest compared to others (A and C − 48%). According to the Casagrande soil classification, soil B was categorized as a silt of high plasticity MH while soils A and C had intermediate plasticity (MI). Several factors such as geomaterial size and shape can induce variations in Atterberg limit values. According to [14], the engineering properties of fine soils such as silts and clay are highly influenced by their shape rather than size of particle. Fine soils such as clay and silts are usually flaky plates in shape. The variation in the Atterberg limit may be the result of the different flaky shapes mixed with other materials that cause the water content to change for all the soil tested. Thus, under such circumstances, the geotechnical properties are naturally variable.

Specific gravity (G_S) for each soil sample was obtained using a 50 ml specific gravity bottle. The test was carried out thrice on each soil sample (A, B, and C) for averaging purposes. It was found that the G_S of soil A (2.10) was greater than the G_S of soil C (2.03) and B (1.98). The G_S value showed an expected small overall variance of ± 0.07 between A, B, and C for the same type of soil (Clayey silt). It is noteworthy that the G_S values obtained were small and in the range 1.98-2.10, commensurate with the very shallow soil sampling and the very probable consequential influence of organic matter content (e.g., plant roots, etc) in the top soil. The loss on ignition (LOI) for the samples were in the range of 2.12 to 4.41%. The value of G_S enables the determination of void ratio and porosity of the soil. In this study, the lowest void ratio e and porosity η were observed in soil A (e = 0.246 and η = 0.198) compared with that in soil C (e = 0.316 and η = 0.240) and in B (e = 0.313 and η = 0.238). The variation of void ratio and porosity between soil A and soil B and C was markedly different compared to the small void ratio and porosity variation between soil B and C. This may be because the degree of compaction of A, B, and C may not exactly be the same. Physically, the lower void ratio and porosity may indicate that the soil was in the dense condition, and vice versa.

The sand replacement method was adopted to determine the field density ρ_{bulk} and ρ_{dry} at the sampling points: the density value at point A (ρ_{bulk} = 1.692 Mg/m^3 and ρ_{dry} = 1.249 Mg/m^3) was greater than at points 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). The density value variation for all points was not significantly large due to the close similarities of soils (ρ_{bulk} variation = 0.175 Mg/m^3 while ρ_{dry} variation = 0.229 Mg/m^3). 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%). The composition of the soil at point B, which has the highest quantity of fine soil, can explain the reason for its having the highest moisture content. Furthermore, the coarseness of the soil contributes to the lower moisture content due to its ability to drain or evaporate water more rapidly compared to fine soil.

3.3. General Relationship between Field ERV and BGP

The results from field ERV and BGP were analyzed statistically and presented as a bar chart in order to demonstrate the general relationship of field ERV with BGP. Similar findings were reported in important pilot studies used to establish a correlation between ERV and BGP for a further stage such as the correlation between ERV with moisture content, density, unit weight, etc. [1, 18-23]. The resistivity value is highly influenced by the characteristics of the pore fluid and the grain matrix structure of geo materials [24]. Hence, the field ERV can give varying values due to the variation in the geo environment, leading to a corollary that BGP strongly influences the field ERV through soil composition, structure, and geochemistry.

As seen in Fig. 4, the high field ERV corresponds to the lower moisture content, and vice versa. The highest field ERV was observed at soil sampling site A (46 Ωm), being a consequence of the location with the least moisture content (35.52%). Conversely, the highest moisture content (48.68%) gave rise to the lowest field ERV (29 Ωm) at location B. Electrical currents propagate in geo materials via the process of electrolysis where the current is carried by ions at a comparatively slow rate [25]. Theoretically, in the application, the water content in subsurface materials has a close positive correlation with the electrical conductivity [26]. This research establishes, via observations and the above discussion, a general relationship where the field ERT is inversely proportional to the amount of moisture content ($\rho \propto 1/w$).

ERV is further influenced by soil grain size since a higher ERV was observed in the larger coarse soil, and vice versa [27]. Figure 4 shows that the highest field ERV was at sampling location A (46 Ωm), which incidentally has the greatest amount of coarse soil (CS) (24.19%) and lowest fine soil (FS) (75.81%). Furthermore, the lowest field ERV was at location B (29 Ωm) which comprised soil with the lowest coarse soil (20.51%) and highest fine soil (79.49%). Hence, it can be concluded that the field ERV is influenced by the soil grain size, following the general relationship that the field ERT was linearly proportional to the amount of coarse soil, and inversely proportional to the fine soil content ($\rho \propto$ CS; $\rho \propto$ 1/FS).

Figure 5 shows that the soil at A (ρ_{bulk} = 1.692 Mg/m^3 and ρ_{dry} = 1.249 Mg/m^3) was the densest (both ρ_{bulk} and ρ_{dry}), followed by soils 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). Void ratio and porosity can influence soil density since a denser soil has a low void ratio and porosity. Moreover, large amounts of water are present in soil with high 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 current propagation (the electrolysis process is difficult in soil with low porosity, which contains 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 $\rho \propto \rho_{bulk/dry}$.

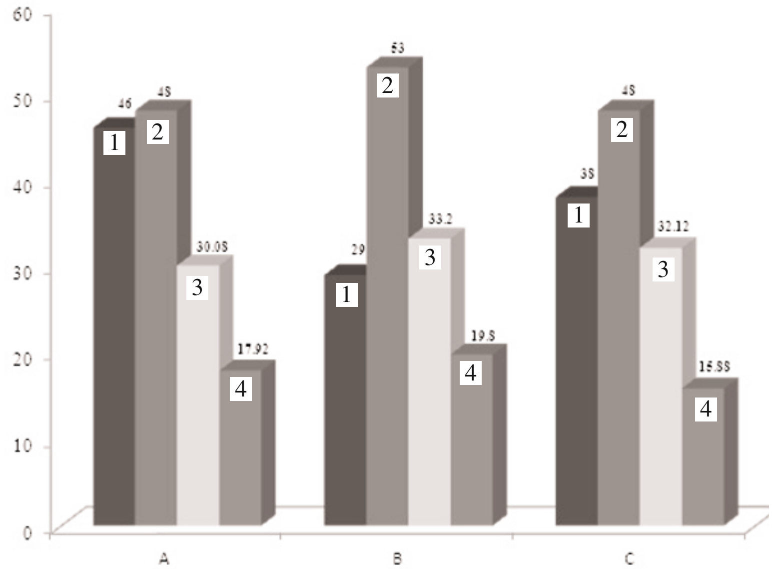

Fig. 6. Relationship of field ERV to the Atterberg limit: 1) field electrical resistivity ρ, Ωm 2) *LL*, %; 3) *PL*, %; 4) *PI*, %.

Figure 6 demonstrates the relationship of field ERV to the Atterberg limit (AL). AL parameters are strictly governed by the fine grained fraction of the soils, reflecting the clay mineralogy and the proportions of clay, silt, and organic content. The soil consistency limits (*LL* and *PL*) define the water contents at which it changes from liquid to plastic and plastic to semisolid states respectively. The results from this study show that the field ERV was lowest at sampling location site B (29 Ωm) and corresponded to the highest value of *LL* (53.00%), *PL* (33.20) and *PI* (19.80%). Both soil sampling sites A and C gave larger field ERV, where the AL properties were lower compared to that of soil B. Hence, the general relationship of field ERV to the Atterberg limit can be established as $\rho \propto 1/\text{AL}$.

However, in some cases, these general relationships may not prove to be consistent especially when the properties obtained are almost similar to each other. Hence, other major nonsimilar properties will override the separate influences on the field ERV. Detailed study under more controlled laboratory conditions than in the field, influence of BGP such as porosity, degree of saturation, salt concentration in pore fluid, grain size, size gradation, temperature, and activity can produce more accurate and consistent correlations [28]. This study has thus attempted to show how field ERV measurements are influenced by a multitude of BGP variations. The discussions from this study will be beneficial to enhancing the understanding of personnel who use the electrical resistivity technique (ERT) as a strong basis for ground investigations. Conventional subjective anomaly interpretations of field ERV can therefore be enhanced using the BGP relationship, thus increasing the sense of appreciation and confidence level of engineers in appliying ERT in geotechnical site investigation (GSI). Moreover, the reliability of field ERV can also be increased objectively due to the strong direct data verification (BGP). According to [2], geophysical techniques offer the opportunity to overcome some of the problems inherent in the more conventional ground investigation techniques. Hence, further research can be extended in the future to the application of ERT as a tool to predict the BGP quantitatively. Currently, the GSI technique is growing rapidly and therefore necessarily requires an alternative tool such as ERT in order to both assist and enhance the conventional GSI techniques (drilling method). Based on [14], it is important to quantify the BGP numerically for the purpose of geotechnical analysis and design. Furthermore, BGP can also influence geotechnical engineering properties such as shear strength and compressibility. ERT can benefit our sustainable ground investigation since it can reduce time, and money and complement other conventional methods, especially through its surface (nondestructive) 2D/3D technique of investigation.

4. Conclusion

The relationship between ERV and BGP was successfully demonstrated specifically on a clayey silt soil. All relationships showed that the BGP influences the ERV either directly or inversely. The field ERV was influenced by the variation in the geo environment, which is related to the composition of water, air, and solid in soil. The establishment of BGP from geotechnical testing and formulation can definitely be applied to verify the field ERV in order to improve and increase the interpretation and reliability of field ERV.

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