# Integration of Vertical Electric Sounding (VES) and Standard Penetration Test (SPT) for Geotechnical Investigation of Subsurface in Phuket

**Solina Keo**

**A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Science in Earth System Science (International Program)**

**Prince of Songkla University**

**2022**

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**Major Program** Earth System Science (International Program)

**Academic Year** 2021

# ABSTRACT

For geotechnical investigation, the electrical resistivity method (ERM) and conventional methods have been accepted. There has been a growing interest in the integration of ERM and conventional methods. Phuket is a popular tourist destination, and the island's rapid infrastructure development is causing growing concern. The purpose of this research is to determine the relationship between electrical resistivity using ERM and geotechnical parameters for sand layers in Phuket, including SPT data, corrected N-value, and estimated geotechnical parameters (share wave velocity, friction angle, young's modulus, and relative density). In addition, data were classified continuously based on geological and seasonal classifications. Using the Pearson correlation method, this study analyzed the relationship between electrical resistivity using ERM and geotechnical data. This study investigated the model function for estimating geotechnical parameters from electrical resistivity using the least square method. Electrical resistivity was found to be correlated with geotechnical parameters on sedimentary and metamorphic rocks during the same seasons of SPT and VES deployments for sand layers in Phuket. Electrical resistivity and geotechnical parameters have a moderate, negative, and statistically significant relationship. Thus, as an indirect predictor of geotechnical parameters, electrical resistivity using ERM is significant. The correlation between ERM and conventional methods may be affected by geology and seasons. ERM is discovered to be a useful tool for estimating geotechnical parameters in geotechnical investigations of subsurface sand layers in Phuket.

**Keywords**: Phuket, sand layers, geological and seasonal classifications, geotechnical investigation, electrical resistivity, geotechnical parameters

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# CONTENTS

## CONTENTS (Continued)

# CONTENTS (Continued)

# CONTENTS (Continued)

# LIST OF FIGURES

**Figures** **Page**

# LIST OF FIGURES (Continued)

**Figures** **Page**

# LIST OF FIGURES (Continued)

**Figures** **Page**

# LIST OF TABLES

# LIST OF TABLES (Continued)

**Tables** **Page**

# LIST OF TABLES (Continued)

**Tables** **Page**

# LIST OF ABBREVIATIONS

$Dr$ – Relative density

ERM – Electrical Resistivity Methods

ERS – Electrical Resistivity Survey

ERT – Electrical Resistivity Tomography

$E_s$ – Young's modulus

ft. – feet

in. – inch

IP – Induced Polarization

kg – kilogram

m – meter

mm – millimeter

N – N-value

$N_{60}$ – Corrected N-value

$r$ – Pearson correlation coefficient

$R^2$ – Coefficient of determination

Sig. – Significance

SPT – Standard Penetration Test

VES – Vertical Electrical Sounding

$V_s$ – Shear wave velocity

vs. – Versus

$\emptyset$ – Friction angle

# CHAPTER 1
# INTRODUCTION

## 1.1 Background of the Study

The number of infrastructures in the world is increasing due to population growth. The needs of buildings, roads, bridges, and other types of facilities are very important for human life, and the investigation of the surrounding environment and economic value is also important. Construction of an engineering structure requires prior investigation of the chosen site as it can provide information about subsurface characteristics. The subsurface characteristics would be used for the determination of suitable foundation designs.

Geotechnical investigation is a fundamental method for civil engineering to obtain geotechnical parameter estimations of earth materials. To evaluate the general suitability of construction on the ground, site investigation plays a crucial role in generating the properties of soil and ground strata at the site. Thus, the determination of soil properties and the characterization of the subsurface are essential to making great designs for the foundation of engineering applications and achieving successful construction.

A standard penetration test (SPT), also known as a geotechnical investigation, has been established since 1925. It is very popular for use for subsurface soil investigation to obtain soil strength parameters in the design of the geotechnical structure. Soil penetration resistance from SPT, which is crucial, and the number of blows from each soil penetration is counted as a blow count, called "N value." The SPT N value at various depths in the borehole provides information about the resistance of soil to penetration. Thus, the various soil parameters such as relative density, angle of friction, cohesion, compaction, and water content can be assessed by soil samples for laboratory tests taken by SPT. However, SPT data and laboratory tests are time-consuming and costly. That is a result for estimation of geotechnical parameters from SPT data, including relative density, Young’s modulus, angle of friction, and shear wave velocity (Bowles, 1996; Cubrinovski & Ishihara, 1999; Denver, 1982; Dikmen, 2009; Hatanaka & Uchida, 1996; Idriss & Boulanger, 2003; Imai, 1977; Kumar & Pasupula, 2019; Lee, 1990; Ohsaki et al., 1959; Papadopoulos, 1992; R. B. Peck et al., 1953; Skempton, 1986; Sykora & Stokoe, 1983; Terzaghi et al., 1996).

The basic concept of electrical resistivity was established in 1912 by the Schlumberger brothers, Conrad and Marcel Schlumberger (Loke, 2015). In the earlier industries, the implementation of the electrical resistivity survey was in petroleum and mining. Later, the linear array of four equal-spaced electrodes was initiated in 1916 by Winner (Loke, 2015). Some of the research studies have shown that an electrical resistivity survey (ERS) is an effective method to generate a view of the beneath profile in a geotechnical investigation.

Vertical electric sounding (VES) is one method of ERS that is a very attractive tool for investigating the properties of subsurface and ground strata. This method has been applied all over the world for three primary purposes, such as mineral exploration, groundwater exploration, and geotechnical investigation (AGIUSA, 2016). VES can be performed using several electrode configurations depending on the defining purposes.

The soil electrical resistivity is determined by measuring the resistance of soil to the flow of electricity. The measurement of apparent resistivity is related to various geological parameters: water saturation, porosity, fluid content, mineral content, and temperature. The flow of electric current in earth materials at a shallow depth occurs through two main methods: electrolytic conduction and electronic conduction (Loke, 2015). In electrolytic conduction, the current flow is via the ion movement in groundwater (Loke, 2015). In electronic conduction, the current flow is via free electrons (like in the metal) (Loke, 2015). Then, electrolytic action is the main cause of current flow through the soil. The current is injected using the two current electrodes, and the potential is measured by the remaining two potential electrodes, differently. It determines the subsurface layers, layer thickness, ground strata, and water content based on the electrical resistivity of the soil.

## 1.2 Statement of Problem

Phuket Island is one of the provinces in Thailand with rapid development in infrastructure This island is among the destinations with the finest beaches in the world. According to the National Statistical Office, the number of tourists in Phuket has risen from 4,317,312 in 2006 to 12,709,415 in 2016. Also, this island had a population of about 300,737 in 2006 and 394,169 in 2016 (NSO, 2019). The records of the increasing number of tourists each year indicate the needs of infrastructure such as hotels, resorts, condominiums, business centers, and so on. Technically, the characteristic of the subsurface is known as the foundation, and it is very significant for structural analysis in the field of civil engineering.

Geotechnical investigation is a conventional direct method that is costly, time-consuming, heavy equipment and destructive method. To save by funding a low-budget subsurface research that could result in an unsatisfactory site investigation (Ashton & Gidado, 2001; Wazoh & Mallo, 2014; Zumrawi, 2014). This can be a big concern on soil failure when the unfavorable ground condition happens (i.e., steep slope areas). It makes the foundation failure. Then the collapse of the civil engineering structure causes the loss of lives and properties. Also, the cost overrun, and the project will be delayed that outcome from the production of an unsatisfactory design.

Despite the fact that drilling boreholes and SPT are still the most dependable procedures for acquiring strength data in geotechnical investigations, SPT has limitations. Soil boring is met by using SPT to collect soil samples for laboratory testing, which disturbs the physical properties of the soil. It means the original structure of the soil can be disturbed. Thus, SPT and soil samples for laboratory tests made by sounding are considered a destructive method. Conducting the SPT to take soil samples in the field, it is not easy and practical to move huge and heavy equipment. Surprisingly, site investigation has access limitations in mountainous, slope area, and rural areas. Then, time-consuming tasks are required to transport the bulky equipment and to set up the equipment for site investigation. To produce the results from the conventional method, which uses expensive equipment. A high budget plan is important to ensure the experts required for conducting the test. Also, the application of SPT to gravels, cobbles, and cohesive soils is limited (British Standards, 2010).

Due to these issues, the ERS provides a non-destructive, simple-to-use, time-saving, and cost-effective method of measuring SPT in borehole and laboratory soil testing. As known, the delineation of main soil types using an electrical resistivity survey can provide information on soil properties and the head of bedrock. The greatest advantage of an ERS is that it is a non-destructive method. This method does not disturb the structure of the sub-soil at the site because it simply injects current into the ground to measure resistance. Then, the equipment for electrical resistivity is light and mobile for easy site investigation. It takes less time to make a measurement. Then it is easier to obtain the measurement results, as it is easier for the procedure. To carry on, the equipment for ERM is cheaper than the conventional method to obtain subsurface information. The test of an ERS can be practical for a variety of soil conditions.

Meanwhile, VES is a simple, non-destructive method for determining the depth to the rockhead for foundation purposes. It also provides data on the saturation level of subsurface materials. (Kearey et al., 2002). Rockhead is the upper boundary of the bedrock formation. Bedrock is the relatively hard, and solid rock beneath surface materials such as gravel and soil (National Geographic Society, 2013). Applying VES in geotechnical investigation can provide geotechnical information. It is a necessary understanding of the properties of subsurface and ground strata. The variation of resistivity in depth can be used to calculate the performance of VES in vertical changes.VES provides subsurface information and accurately. It includes information on estimation of depth, thickness, and resistivity of subsurface layers as well as a layered resistivity model.

Moreover, there is no explanation of the causes of the relationship electrical resistivity with geotechnical parameters from estimation studies (i.e., electrical resistivity vs. N-value and friction angle). Hence, this study aims to figure out the cause of the correlations between ERM and conventional methods.

The relationship between electrical resistivity and geotechnical parameters will improve application between the ERS and conventional investigations. The electrical resistivity value will be interpreted to apply to geotechnical design that makes ERM more effective for subsurface investigation. However, there is a lack of studies about correlation analyses between resistivity and geotechnical data for geotechnical investigation purposes in Phuket. Thus, this study has three different research objectives regarding the integration of VES and SPT for geotechnical investigation of the subsurface in Phuket.

## 1.3 Research Objectives

- To determine the relationship between electrical resistivity using ERM and geotechnical parameters for sand layers in Phuket.
- To expose the effects of geology and seasoning on the correlation between ERM and conventional methods (SPT method) for geotechnical parameter estimations.
- To propose geotechnical parameter estimations using ERM as an alternative tool for sand layers in Phuket.

## 1.4 Research Scopes

**Area**

- This study was conducted in Phuket, Thailand, with the coordination of the latitudes 7°45′ and 8°15′N and longitudes 98°15′ and 98°40′E.

**Method**

- The ERM using the VES technique was conducted to obtain electrical resistivity data for sand layers in Phuket.
- For sand layers in Phuket, the Pearson correlation analysis approach was used to assess the link between electrical resistivity and geotechnical characteristics.

**Time**

- This study was taken to complete from 2018 to 2021.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Introduction to Subsurface Investigation

The primary goal of the subsurface investigation is to provide specific, reliable and detailed information about the site's soil, rock, and groundwater conditions (Rix et al., 2019). It may be necessary for the safe and cost-effective design and execution of engineering works (Rix et al., 2019). The scope of site investigation is generally based on time constraints and budget plans placed on the investigation and the experience and judgment of the geotechnical engineer (Zumrawi, 2014).

Geological forces and processes produce inhomogeneous and discontinuous soil formations that affect the stability and cost of civil engineering projects. Based on estimation and judgment on soil information, it can be characterized by the site economically and the type and methods of construction properly. It also provides information about natural geological hazards, especially about groundwater conditions. Soil information is then a necessary part of the design and construction of a proposed structural system such as buildings, roads, highways, dams, and so on (Rix et al., 2019).

Inadequate engineering site investigation typically poses the greatest risk because adverse subsurface conditions or unfavorable ground conditions can have significant impacts on life-cycle costs, project schedules, public safety, and environmental sustainability (Rix et al., 2019; Wazoh & Mallo, 2014).

In situ testing is one of the geotechnical methods to investigate the subsurface. However, this conventional direct method is costly, time-consuming, and requires heavy equipment. Consequently, the indirect non-destructive geophysical method like electrical resistivity survey is being used increasingly in integration with geotechnical investigations such as in situ tests and borehole tests (Devi et al., 2017).

## 2.2 Geotechnical Investigation: In-situ tests

In-situ testing refers to geomaterial testing while it is still in the subsurface (Rix et al., 2019). It is opposed to the usual approach of extracting samples from boreholes, and transferring them to a laboratory for testing (Rix et al., 2019). In general, in-situ tests are faster than laboratory tests because the findings can be acquired on-site right away.

Field data is gathered using a variety of in-situ tests. It defines layers, zones, soil strata, and stratigraphy in a more thorough way. It can also be used to identify lenses, weak zones, and inclusions. Field testing also allow for an assessment of vertical and horizontal variability to see if there is overall homogeneity or heterogeneity across a site. In addition, the tests give an independent assessment of geotechnical engineering parameters for analysis and design. For assessing and characterizing the subsurface, a wide range of in-situ experiments has been established.

## 2.3 Standard Penetration Test (SPT)

The SPT was introduced by the Raymond Pile Company in the United States of America in 1902, and the test was developed in 1927 (Rogers, 2006). The earliest reference to a procedure for SPT was written in a paper by Terzaghi in 1947 (Rogers, 2006). However, the test became the standard in the USA in 1958 (Rogers, 2006). The method of SPT is based on the American Society of Testing and Materials (ASTM), and it is detailed in ASTM D1586 (Rogers, 2006). The SPT, which is one of the simplest and cheapest, is still in use today all over the world (Kulhawy & Mayne, 1990).

The SPT is used to obtain an estimated measure of dynamic soil resistance and a disturbed soil sample during a borehole drilling test (Rix et al., 2019). It is most commonly used to determine the shear strength of strong sandy soil and over-consolidated clay (Rix et al., 2019). The test can be used on a wide range of soils (Rix et al., 2019). However, SPT results are unreliable for some soil types. There is coarse gravel, cobbles, boulders, cohesionless silts, and soft, delicate clays (Kulhawy &

Mayne, 1990; Rix et al., 2019). The most consistent results using SPT were discovered in sandy soil where large gravel particles are absent (Kulhawy & Mayne, 1990).

2.3.1 Procedure for Standard Penetration Test

The necessary equipment for the test procedure is located in the general layout of the SPT (Rix et al., 2019; Wazoh & Mallo, 2014). It includes a hammer system, drill rods, and a split-spoon or split-barrel sampler, as shown in Figure 2.1 (Rix et al., 2019; Wazoh & Mallo, 2014).

To perform the test, given in Figure 2.2, SPT entails the driving of a thick hollow tube (Mayne et al., 2001). The inside diameter of the tube is 35mm (1.38in.) and the outside diameter is 51mm (2.0in.) (Mayne et al., 2001). It extends approximately 450mm into the ground (18 in. = 457mm) (Mayne et al., 2001). It keeps track of how many blows are required to drive each 150mm (6in.) increment (Mayne et al., 2001). For the pounding, a drop weight system is used, in which a 63.5kg hammer (Mayne et al., 2001). Then it is repeatedly dropped from a height of 762mm (30in.) to achieve three successive 150mm increments (Mayne et al., 2001). The sampler is seating is indicated by the first increment. The number of blows required to advance the second and third increments is added to give the N value or SPT resistance (Mayne et al., 2001). Thus, the number of blows required to advance the split-barrel sampler 300mm (12in.) vertically or blows per foot (Mayne et al., 2001).

If the sampler is unable to be driven 450mm, the number of blows per increment and partial increment are recorded on the boring log (Mayne et al., 2001). Additionally, the depth of penetration is noted in relation to the number of blows. The test is typically carried out at 1.5m (5ft) depth intervals (Rix et al., 2019). It is frequently less than 0.75m (2.5ft) at shallow depths of less than 3m (10ft) (Rix et al., 2019).

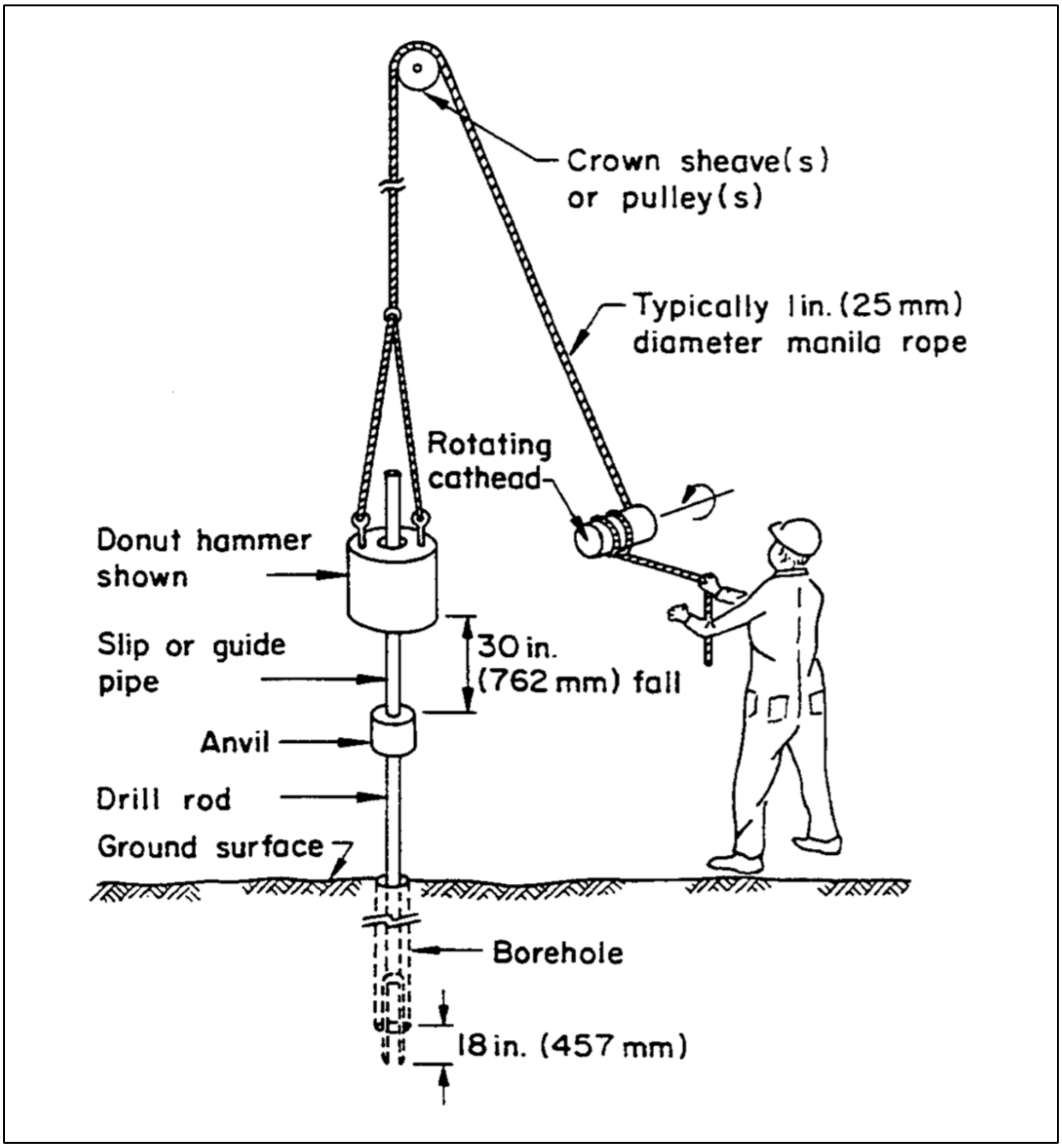


Figure 2.1 Equipment for performing SPT (Kulhawy & Mayne, 1990)

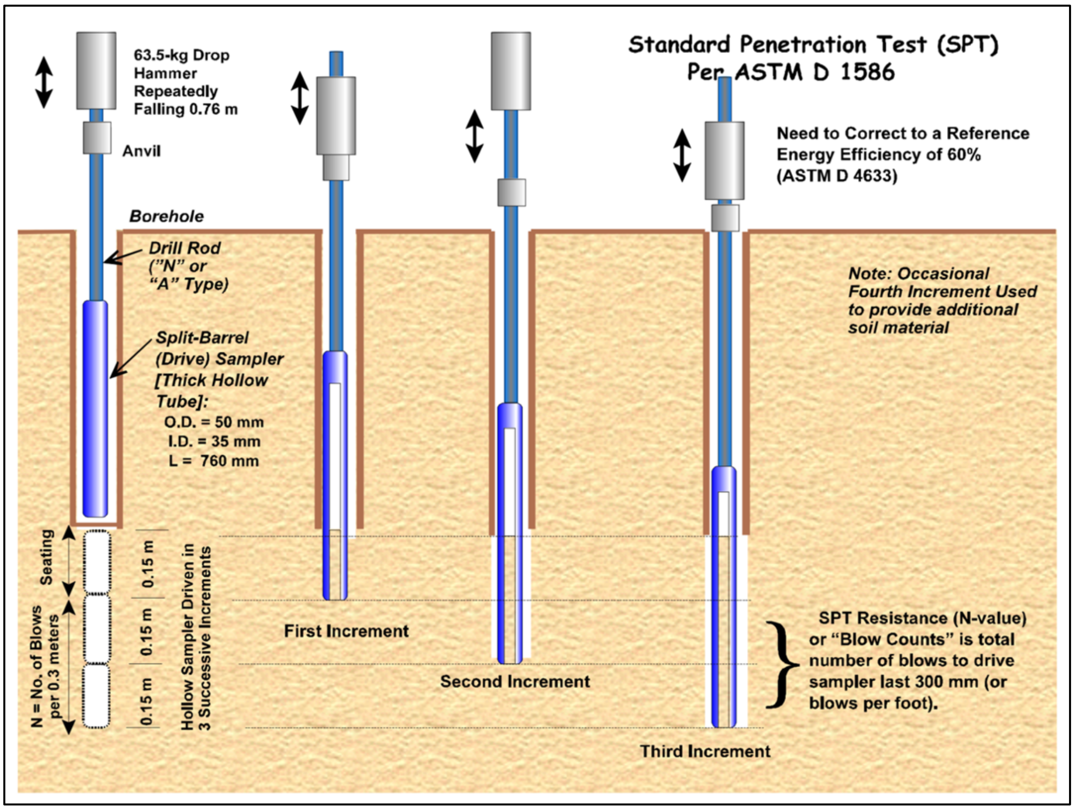


Figure 2.2 Sequence of driving split-barrel sampler during SPT (Mayne et al., 2001)

### 2.3.2 Advantages and Limitations of Standard Penetration Test

There are some advantages to the standard penetration test (SPT) that are noted. SPT is a popular test used in geotechnical method, and it is widely available for usage in many projects worldwide (Al-Jabban, 2013). It is relatively inexpensive, which is different from other geotechnical methods. Then, this test can obtain both a number and a sample of soil test the results, from which the sample can be transported to the laboratory for deriving other geotechnical parameters. Following that, SPT is suitable for a wide range of soil types. Also, it is applicable in weak rock as it can penetrate relatively difficult materials that are as hard as dense layers and gravel. After that, SPT is relatively quick, simple, and rugged in comparison with other in-situ geotechnical tests that are easy to process to receive the filed data on-site. As a result, SPT is an important instrument for assessing the relative strength and compressibility of soil in a test region (Al-Jabban, 2013; Kulhawy & Mayne, 1990; Mayne et al., 2001).

Furthermore, SPT has the highest reliability (Kulhawy & Mayne, 1990). It is used as an index test to determine the approximate strength and compressibility of sandy soil strata for preliminary design purposes (Kulhawy & Mayne, 1990). For example, soil with a N value of 50 is unlikely to present significant problems in terms of strength or compressibility for spread footings (Kulhawy & Mayne, 1990). However, soil with a N value of 2 or 3 is likely to present a significant number of challenges (Kulhawy & Mayne, 1990).

The limitations of the SPT still remain as the test has many sources of error, both random and systematic (Kulhawy & Mayne, 1990). As the test's accuracy, SPT has a high level of variability and uncertainty (Mayne et al., 2001). It is heavily influenced by the procedure used and the equipment used by the drilling crew (Rogers, 2006). Thus, drillers' care and knowledge play an important role in forming a critical factor in test accuracy (Mayne et al., 2001). Then, both a number and a sample were obtained simultaneously, which made the results of poor quality. After that, SPT has little meaning in soft clays and silts as they exhibit different driving resistances once moist or dry. These lead to erroneous strength and compressibility determinations that impact on SPT results that are inconsistent with actual in-situ conditions. Furthermore, when coarse gravel, cobbles, or boulders obstruct the sampler, SPT can produce an erroneously high and unconservative N value (Kulhawy & Mayne, 1990). When the water level in the hole is not maintained at or above the groundwater level, the soil can become loosened, invalidating the test results, because piping can appear at the bottom of the hole, affecting the soil. This problem is solvable. Before performing SPT, it must return water to the hole after the drilling equipment has been removed (Kulhawy & Mayne, 1990; Mayne et al., 2001; Rogers, 2006).

In addition to the sources of error that are given in Table 2.1, the test results and the correlations of N value with engineering properties are affected by a number of soil mechanics factors. These factors include particle size, shape, and mineralogy; soil sensitivity, permeability, and degree of saturation; time lapse between drilling and testing; the spacing of samples; depth of sampler penetration; relative depth of the boring; and the size of the vent area of the sampler (Kulhawy & Mayne, 1990).

Table 2.1 Major source of error in SPT (Kulhawy & Mayne, 1990)

| Major sources of error in standard penetration test (SPT) | | | |
|---|---|---|---|
| **No.** | **Cause** | **Effect** | **Influence on N value** |
| 1 | Inadequate cleaning of the hole | SPT is not made in original in-situ soil, and therefore soil may become trapped in a sampler and be compressed as the sampler is driven, reducing recovery | Increases |
| 2 | Failure to maintain the adequate head of water in the borehole | Bottom of the borehole may become quick | Decreases |
| 3 | Careless measurement of hammer drop | Hammer energy varies (generally, variations cluster on the low side) | Increases |
| 4 | Hammer weight inaccurate | Hammer energy varies (driller supplies weight; variations of 5 to 7 percent are common) | Increases or decreases |
| 5 | Hammer strikes drill rod collar eccentrically | Hammer energy-reduced | Increases |
| 6 | Lack of hammer free fall because of ungreased sheaves, new stiff rope on weight, more than two turns on cathead, the incomplete release of the rope during each drop | Hammer energy-reduced | Increases |
| 7 | Sampler drove above the bottom of the casing | Sampler drove in disturbed, artificially densified soil | Increases greatly |
| 8 | Careless blow count | Inaccurate results | Increases or decreases |

**2.4 Correction of SPT N-value**

The SPT is an in-situ test that is used to determine the geotechnical engineering properties of soil (NovoSPT, 2021). Various SPT equipment have been developed for different types of drilling and applications depend on different situations (NovoSPT, 2021). SPT blow counts from the field must be corrected (NovoSPT, 2021). For use of the SPT correction factor, the SPT N-value correction for field procedures (energy correction) is always appropriate (NovoSPT, 2021). However, SPT N-value correction for overburden pressure may or may not be appropriated (NovoSPT, 2021). It is depending on the procedures by those who developed the analysis method under consideration (NovoSPT, 2021).

Based on the field observations, it appears reasonable to normalize the field SPT N-value as a function of the input driving energy and its dissipation around the sampler and surrounding soil (Naing, 2010; NovoSPT, 2021). Variations in the test procedures can be compensated for in part by converting measured N to corrected N (N60) (Naing, 2010; NovoSPT, 2021). It is following as (Naing, 2010; NovoSPT, 2021):

$$N_{60} = N.C_E.C_B.C_S.C_R \tag{2.1}$$

Where,

$N$ = SPT measured N-value in the field

$N_{60}$ = SPT corrected N-value for field procedures

$C_E$ = energy correction factor for SPT hammer: donut hammer (0.3 to 0.6), safety hammer (0.6 to 0.85), and auto-hammer (0.8 to 1.0)

$C_B$ = borehole diameter correction: 65 to 115mm (1.0), 150mm (1.05) and 200mm (1.50)

$C_S$ = sampling method: standard sampler (1.0) and sampler without liner (1.1 – 1.3)

$C_R$ = rod length correction

The correction factor, rod length ( L ), is determined by the length of SPT rods, which is approximately equal to the depth of the test (NovoSPT, 2021). To account for the distance between the anvil and ground surface, adding one meter is typically enquired to the total test depth for calculating $C_R$: L < 4m (0.7); 4m < L < 6m (0.85); 6m < L < 10m (0.95); L > 10m (1.0).

## 2.5 Geotechnical Parameter Estimations using SPT Data

In geotechnical investigations, researchers have made numerous efforts to establish the estimations of soil parameters at the depth of borehole based on SPT data. Many design parameters of subsurface soil are correlated with N-value, including shear wave velocity, friction angle, Young's modulus, and relative density.

### 2.5.1 Shear Wave Velocity ($\boldsymbol{V_s}$)

Determining shear wave velocity is one of the most important tasks in establishing the design of a geotechnical engineering structure **(**Imai, 1977**).** It is the most important parameter for determining soil layer stiffness (Kirar et al., 2016). Wave propagation tests are commonly used to determine a site's common wave velocity profile (Kirar et al., 2016). Although it is possible to measure it through in-situ field tests, doing so at all of the sites is not economically feasible. Numerous studies propose empirical equations of shear wave velocity with SPT N-value **(**NovoSPT, 2020**).** Table 2**.**2 shows that there is some SPT correlation for sandy soils**.**

Table 2.2 SPT correlation for shear wave velocity ($V_s$) (NovoSPT, 2020)

| **Author(s)** | $\boldsymbol{V_s\ (m/s)}$ |
|---|---|
| Imai (1977) | $V_s = 80.6(N_{60})^{0.331}$ |
| Sykora and Stokoe (1983) | $V_s = 100.5(N_{60})^{0.29}$ |
| Lee (1990) | $V_s = 57.4(N_{60})^{0.49}$ |

### 2.5.2 Friction Angle ($\emptyset$)

Friction angle is one of the most important strength parameters of sandy soils (Terzaghi et al., 1996). Also, the SPT N-value in sandy soil indicates the friction angle in the sandy soil layer (Naing, 2010). Thus, the friction angle is often estimated using empirical equations from SPT data. A list of empirical equations is detailed in (NovoSPT, 2020). Even though the effects of the shape of the soil's grains on the penetration resistance are mentioned (Dunham, 1954), some equations have the common feature that the friction angle is directly related to the N-value. It is shown in Table 2.3.

Table 2.3 SPT correlation for friction angle ($\emptyset$) (NovoSPT, 2020)

| **Author(s)** | $\emptyset$ (**degree**) |
|---|---|
| Peck et al., (1953) | $\emptyset = 28 + \frac{N_{60}}{4}$ |
| Ohsaki et al., (1959) | $\emptyset = 15 + (20N_{60})^{0.5}$ |
| Terzaghi et al., (1996) | $\emptyset = 27 + (0.3N_{60})^{0.5}$ |

### 2.5.3 Young's Modulus ($E_s$)

Young's modulus of soil, commonly denoted as soil elastic modulus, is an elastic soil parameter which is a vital component for foundation design. It is a useful property to evaluate the behavior of the soil material when subjected to a force (Bowles, 1996). The prediction of modulus of elasticity and its impact on settlement have been investigated (Kumar & Pasupula, 2019). The common report of the empirical equations is given in Table 2.4. The young's modulus is directly associated with SPT data. Moreover, there is a list of young people's modulus correlated with SPT, which is presented in (NovoSPT, 2020).

Table 2.4 SPT correlation for young's modulus ($E_s$) (NovoSPT, 2020)

| **Author(s)** | $\boldsymbol{E_s}$ **(MPa)** |
|---|---|
| Denver (1982) | $E_s = 7(N_{60})^{0.5}$ |
| Papadopoulou (1992) | $E_s = \frac{(75+8N_{60})100}{1000}$ |
| Bowles (1996) | $E_s = \frac{6000N_{60}}{1000}$ |

2.5.4 Relative Density ($\boldsymbol{D_r}$)

Relative density is the determination of the compactness of cohesionless soil. Measurement of the relative density is useful in the compaction of coarse-grained soil (Skempton, 1986). For sandy soils, the relative density is helpful in the evaluation of safe bearing capacity. In the case of very dense gravelly sand, it is great to acquire the relative density while the natural dense packing cannot be acquired in the laboratory (Kuenza et al., 2004). Several empirical equations between relative density and SPT data have been found, which are listed in (NovoSPT, 2020). Also, a list of a few equations of SPT correlation for the relative density is shown in Table 2.5.

Table 2.5 SPT correlation for relative density ($D_r$) (NovoSPT, 2020)

| **Author(s)** | $\boldsymbol{D_r}$ **(%)** |
|---|---|
| Skempton (1986) | $D_r = 12.4(N_{60})^{0.5}$ |
| Cubrinovski (1991) | $D_r = 100\left(\frac{(N_1)_{60}}{39}\right)^{0.5}$ |
| Idriss (2003) | $D_r = 100\left(\frac{(N_1)_{60}}{46}\right)^{0.5}$ |

## 2.6 Geophysical Investigation: Electrical Resistivity Survey

The geophysical investigation results are used to estimate the physical properties of the subsurface (Rix et al., 2019). The electrical resistivity survey has its origins in the 1920s due to the work of the Schlumberger brothers, Conrad and Marcel (Loke, 2015). The implementation of the electrical resistivity survey in the earlier industries was in petroleum and mining. After that, the linear array of four equal-spaced electrodes was initiated in 1916 by Wenner (Samouëlian et al., 2005). It is one of the oldest geophysical survey methods. The purpose of ERS is to determine the subsurface resistivity distribution by injecting electric current into the ground (Loke, 2015). The results of injecting from the surface into the ground are measured by the potential difference (Kearey et al., 2002; Loke, 2015; Rix et al., 2019). It is measured via a separate pair of electrodes (Kearey et al., 2002; Loke, 2015; Rix et al., 2019). The potential difference provides information on the form of subsurface inhomogeneities and their electrical properties (Kearey et al., 2002). The resistivity of a material is well-defined as the resistance in ohms (Kearey et al., 2002; Loke, 2015; Rix et al., 2019).

An electrical resistivity traditionally contains four electrodes that are coupled to the ground (Loke, 2015). The depth of penetration depends on the spacing of the electrodes (Loke, 2015). The depth of penetration increases proportionally when the electrode spacing increases (Loke, 2015). The principle of electrical resistivity survey is governed by Ohm's law (Loke, 2015). There are two electrodes that transmit electric current to the ground (Samouëlian et al., 2005). The other two electrodes measure the change in potential in the earth's materials between the two current electrodes (Samouëlian et al., 2005). Then the apparent resistivity ($\rho_a$) is a function of the measured electric impedance (Rix et al., 2019; Samouëlian et al., 2005), as given below.

$$R = \frac{V}{I} \tag{2.2}$$

Where $I$ is an electric current in a unit of an ampere (A), $V$ is potential difference/voltage in a unit of a volt (V), and $R$ is electrical resistance in a unit of an ohm (Ω).

$$\rho_a = kR \tag{2.3}$$

Thus, the electrical resistivity can be calculated where $\rho_a$ is the electrical resistivity in the unit of ohmmeter (Ωm-m), and $k$ is a geometric factor that depends on the array type and spacing of the electrodes. $a$ is electrode spacing. In the case of Wenner arrays, this is $k = 2\pi a$ (Samouëlian et al., 2005).

The resistivity of the ground is related to a variety of geological parameters, including mineral content, fluid content, porosity, and the degree of water in the soil and rock (Loke, 2015). Certain minerals, such as native metals and graphite, conduct electricity by allowing electrons to pass through them (Loke, 2015). In contrast, most rock-forming minerals are insulators, and current is carried through a rock primarily by the passage of ions in pore waters. As a result, the process of conducting electricity is electrolytic rather than electronic. As a consequence, porosity is the primary determinant of rock resistivity. The porosity decreases, the material resistivity increases (Loke, 2015). Because of these influencing factors, the ERS can be used to estimate subsurface layers, strata, and groundwater tables, among other things. The range of electrical resistivity of earth materials is given in Figure 2.3.

ERS has been applied for many decades in various applications such as geotechnical, hydrogeological, mining, hydrocarbon, and environmental surveys (Loke, 2000, 2004, 2015). Due to rapid advances in the software of computers and associated modeling solutions, resistivity surveying has been applied increasingly in engineering practices for geotechnical investigation and groundwater exploration. The ERS, according to certain research papers, is a good approach to generate a perspective of the subsurface profile in a geotechnical study (Samouëlian et al., 2005). Due to the simplicity of techniques, VES has become very popular for the purpose of engineering and groundwater investigation (Jatau et al., 2013).

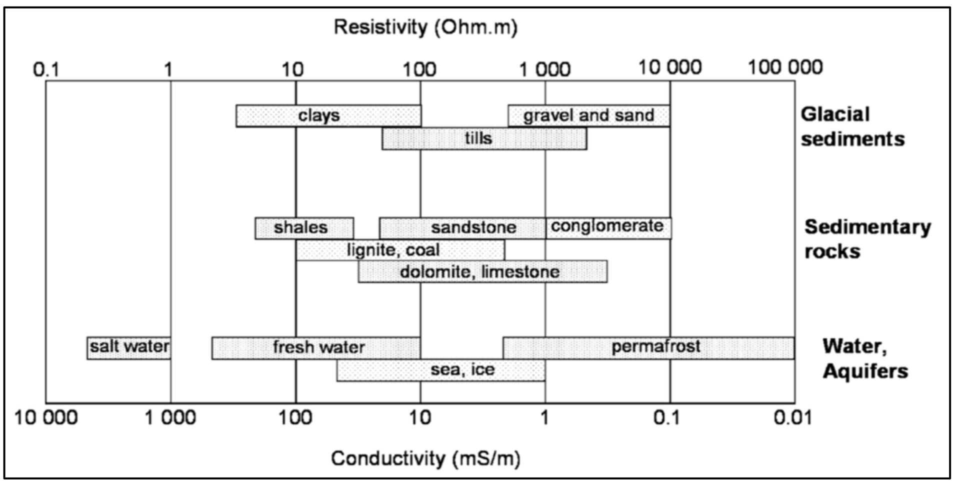


Figure 2.3 The electrical resistivity range of earth materials (Samouëlian et al., 2005)

## 2.7 Vertical Electric Sounding (VES)

VES is a field survey technique used to investigate horizontal or near-horizontal interfaces (Kearey et al., 2002). It is also referred to as a "expanding probe" or "electrical drilling." There are two current electrodes and two potential electrodes. The current and potential electrodes are kept at the same distance apart in relation to each other. The electrode spreads are widened from a central location that is fixed. It enables for readings as the current runs deeper into the ground (Kearey et al., 2002). As a result, electrical measurements are performed in which the distance between the electrodes is gradually increased. As the depth and volume of soil investigated increase, the measurement demonstrates the variation of soil resistivity with depth, which accounts for vertical variation rather than horizontal variation (Samouëlian et al., 2005). The technique is widely used in hydrogeology to depict horizontal zones of porous strata. It is used in geotechnical investigations to determine overburden thickness (Kearey et al., 2002).

ERS is frequently used to conduct engineering geological investigations of potential construction sites. VES is a technique for determining electrical resistivity. VES is a type of electrical resistivity survey that can be used to investigate the properties of subsurface and ground strata. Mineral exploration, groundwater exploration, and geotechnical investigation are the three primary goals of VES (AGIUSA, 2016). This survey is a very convenient and non-destructive method of determining the depth to rockhead for foundation purposes. It also provides information about the degree of saturation of subsurface materials (Kearey et al., 2002; Loke, 2000, 2004, 2015; Samouëlian et al., 2005). VES can be performed using either the Wenner electrode configuration or the Schlumberger electrode configuration, as described in the American Society of Testing and Materials (ASTM) G57 (AGIUSA, 2016). Because it is less labor-intensive than the Wenner array, the Schlumberger array is most commonly used for groundwater exploration and mineral exploration (AGIUSA, 2016). However, the Wenner array is best suited for geotechnical research (AGIUSA, 2016).

### 2.7.1 Wenner Array

In 1912, the Schlumberger brothers of France pioneered the basic concept of electrical resistivity (Kearey et al., 2002). In 1916, Frank Wenner of the

United States pioneered the linear array of four equal-spaced electrodes (Kearey et al., 2002). The electrode configuration was designed with progressive and increasing spacing around an introduced fixed central point (Kearey et al., 2002). The Wenner array is a simple and reliable arrangement (Kearey et al., 2002). All four electrodes are shifted between readings, and the current and potential electrodes are kept at equal spacing (Kearey et al., 2002). The increased potential electrode spacing of the Wenner array puts less strain on instrument sensitivity (Burger et al., 2006). The Wenner array is presented in Figure 2.4.

The depth of examination for the Wenner array can therefore be solved in one of two ways: by spacing or by length.

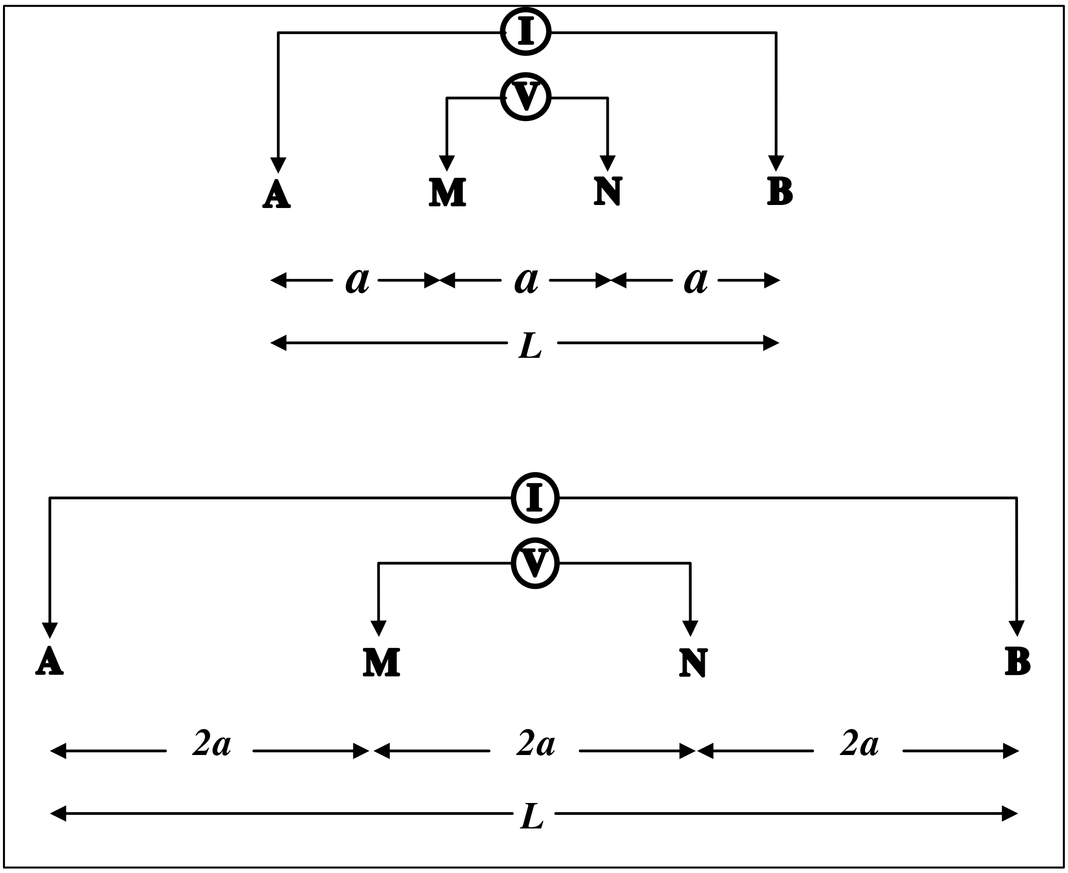


Figure 2.4 Winner array: estimation depth of investigation

The equation to estimate the depth of investigation using spacing or length is:

$$\frac{Ze}{a} = 0.519 \quad \text{or} \quad \frac{Ze}{L} = 0.173 \tag{2.4}$$

Where, $Ze$ is the depth of investigation, $a$ is spacing, and $L$ is length.

The primary advantage of the Wenner array is how it calculates apparent resistivity. In the field, the apparent resistivity can be simply estimated (Loke, 2015). The sensitivity of the instrument is not as important as it is with other array designs (Loke, 2015). Small current magnitudes are also necessary to achieve measurable potential differences (Hassan et al., 2017). The sensitivity of the array, horizontal data coverage, depth of research, and signal strength are some of the array parameters to consider (Loke, 2015). Vertical changes are particularly sensitive to the Wenner array. Deriving the variation of resistivity in depth appears to be a good idea. It is the same as SPT's variation of N value with depth in the borehole. This array is good for resolving horizontal structure detections in the shallow subsurface. The investigation then progresses to a moderate level. It also has the most powerful signal. As a result, the Wenner array yields a more accurate and stable solution (Loke, 2015).

However, the disadvantages of the Wenner array remain. As it has good sensitivity to vertical changes, it is less sensitive to horizontal changes. It is good at resolving horizontal structures, yet it is poor at detecting narrow vertical structures (Loke, 2015). When the sound measurement is finished, all of the steel electrodes must be moved to a new position for each sound. To image deep into the ground, longer current cables must be used. Handling the steel electrodes and cables between each sounding measurement can be difficult, particularly in difficult terrain. Furthermore, because the Wenner array is sensitive to near-surface homogeneities, it may skew deeper electrical responses (Hassan et al., 2017).

2.7.2 Advantages and Limitations of Vertical Electric Sounding

VES, a known geophysics method, is a nondestructive method for investigating the subsurface without disturbing the physical structure at the site of investigation (Devi et al., 2017). Testing by injecting the current from the surface into the ground offers the ability to cover a large area for the understanding of the overall subsurface conditions (Mayne et al., 2001). VES is a simple survey that yields good results when certain survey criteria are met (AGIUSA, 2016). As an electrical resistivity survey, VES uses the theoretical basis for information to interpret the result. Moreover, VES is applicable to sites where borings and soundings are difficult or impractical, i.e., contaminated soil or gravel deposits (Rix et al., 2019). This is due to the ability of VES to detect subsurface information by flowing current through soils and rocks (Mayne et al., 2001).

As an indirect method, VES has no samples for transport to the laboratory. It uses models assumed for the interpretation of results. The results can be affected by cemented layers or inclusions because of the large stiffness of the cement. Also, the results can be influenced by depth, clay, and water.

### 2.8 Using Electrical Resistivity Survey for the Geotechnical Purpose

Electrical resistivity correlation with geotechnical parameters has been increasingly investigated due to the usefulness of electrical resistivity survey for geotechnical engineering. This is due to the fact that subsurface electrical resistivity has been shown to be related to a variety of geotechnical properties. Soil strength, saturation, volumetric water content, salt content, clay content, void ration, bulk density, unit weight, liquid limit, plasticity index, porosity, remoulded shear strength, and degree of compaction are among them (Giao et al., 2003; Kibria & Hossain, 2012; Lin et al., 2017; Long et al., 2012).

Several earlier investigations have found a link between electrical resistivity and geotechnical data on subsurface characterization (Akinlabi & Adeyemi, 2014; Mohammed et al., 2019; Osman et al., 2016; Rezaei et al., 2018). The electrical resistivity and conductivity are dependent on the degree of compaction, according to the research (Bryson, 2005; Kowalczyk et al., 2014). The degree of saturation and the amount of water present have been discovered (Cosenza et al., 2006; Hatta & Syed Osman, 2015; Liu et al., 2008; Syed & Siddiqui, 2012).

For subsurface study, the use of ERS in conjunction with geotechnical technologies like SPT has risen (Devi et al., 2017; Hatta & Syed Osman, 2015; Kalyane, 2017; Oh & Sun, 2008; Rezaei et al., 2018; Syed & Siddiqui, 2012; Tan et al., 2018). There is no rule of thumb that the electrical resistivity value of soil has a linear relationship with the SPT N-value, according to prior studies. Electrical resistivity and SPT N-value have been found to have a positive linear connection (Devi et al., 2017;

Hatta & Syed Osman, 2015; Liu et al., 2008). A weak linear relationship has also been discovered (Akinlabi & Adeyemi, 2014). In the Rio Claro and Corumbata Formations of Paran's sedimentary basin, a poor exponential relationship between electrical resistivity and SPT N-value was observed (Braga et al., 1999). He also claimed that by removing the arid zone with high resistivity from 0.3 to 0.7, the correlation coefficient can be improved. Some data show a positive, negative, and inconsistent relationship between electrical resistivity and SPT N-value and sedimentary area (Tan et al., 2018). The number of blows reduces soil resistivity (Razali & Osman, 2011).

The electrical resistivity with other geotechnical parameters is also important for geotechnical engineering investigation. Some articles have shown the study between electrical resistivity and friction angle (B. Syed Osman & I. Siddiqui, 2015; Boobalan & Ramanujam, 2015; Siddiqui & Osman, 2013, 2012). A positive relationship has been mentioned (Osman et al., 2014; Qazi et al., 2016; Razali & Osman, 2011), while a negative relationship has been found in clayey sand (Bery, 2016; Bery & Saad, 2012). Some researchers have used vertical electric sounding (VES) as a method to obtain electrical resistivity to correlate with friction angle (Boobalan & Ramanujam, 2015; Osman et al., 2016; Siddiqui & Osman, 2013). Meanwhile, the negative empirical relationship between electrical resistivity and seismic velocity ($V_p$) (Bery & Saad, 2012). Also, there is an implement of VES and seismic velocity for a landslide area in southeastern Korea (Kim et al., 2011). However, a lack of work has been carried out for other geotechnical parameters to correlate with electrical resistivity, which include shear wave velocity, young's modulus, and relative density.

The employment of electrical resistivity survey has been done in Phuket for the determination of the subsurface in Phuket (Giao et al., 2005; Nontapot et al., 2019; Puttiwongrak et al., 2019; Puttiwongrak, Men, Vann, Hashimoto, et al., 2022; Tesfaldet & Puttiwongrak, 2019; Vann et al., 2020). An electric imaging survey was utilized in site investigation for reconstruction due to an emergency response to a tsunami affected (Giao et al., 2005). The use of electrical resistivity imaging (ERI) and induced polarization (IP) has been implemented to detect the contamination level from tin mining (Puttiwongrak et al., 2019). In Phuket, a groundwater potential map was created by combining a geoelectrical survey and time-lapse resistivity data with groundwater data (Puttiwongrak, Men, Vann, Hashimoto, et al., 2022). Seasonal groundwater recharge has been estimated using time-lapse ERT (Tesfaldet & Puttiwongrak, 2019). Then, delineation of seawater intrusion was done in a coastal aquifer of Phuket (Vann et al., 2020).

However, using VES to study the relationship between electrical resistivity and geotechnical parameters for geotechnical investigation in Phuket is lacking. Since then, there have been some publications that have presented the use of VES for geotechnical purposes in different locations, namely lithological variations of dam foundations, geoelectric layers for evaluation of road failure vulnerability sections, and construction purposes (Adebisi et al., 2016; Adeoti, 2013; Adiat et al., 2017; Akinlabi & Oladunjoye, 2008; Oyedele et al., 2011).

# CHAPTER 3
# METHODOLOGY

## 3.1 Description of Study Area

Phuket is an island that has a location in the south of Thailand, which is situated on the Andaman Sea, shown in Figure 3.1. It is approximately 870 kilometers from Bangkok, with latitudes of 70 45' N to 80 10' N and 980 15' E to 980 30' E, and covers an area of approximately 543 km2. This area is in a humid tropical zone that experiences high rainfall with long periods of high temperatures (Saunders & Fookes, 1970). Then most parts of this area are covered by granite, which is a kind of igneous rock.

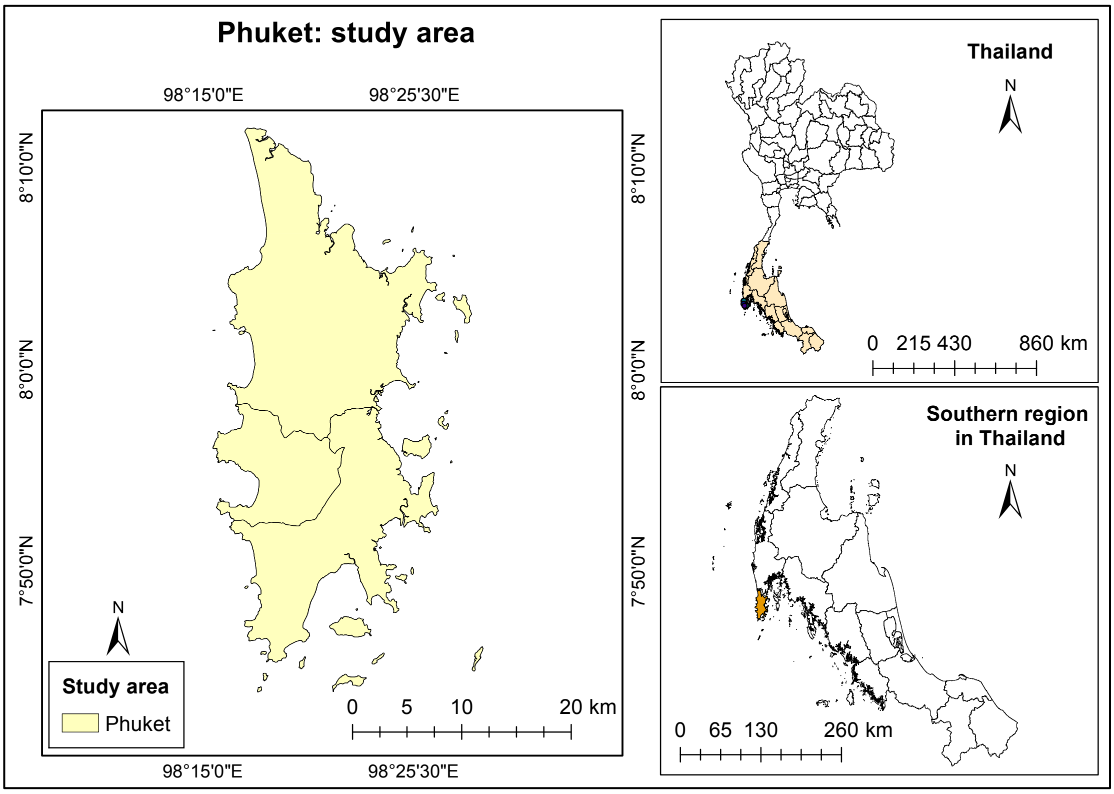


Figure 3.1 Map of Phuket

However, there is a lack of research work that studies the subsurface in Phuket by integrating VES and SPT as research methodologies. According to the existing data of SPT in different locations in Phuket, namely Mai Khao, Choeng Thale, Ratsada, and Kathu, as given in Table 3.1. ERS using VES lines was conducted at the station nearby the SPT stations, which has been carried out for geotechnical investigation in Phuket. The map showing the study area location is shown in Figure 3.2.

Table 3.1 Coordinate of study area in Phuket

| **No. Location** | **Study Area** | **Latitude** | **Longitude** |
|---|---|---|---|
| 1 | Mai Khao | 8.13360°N | 98.30013°E |
| 2 | Choeng Thale | 7.99233°N | 98.29512°E |
| 3 | Ratsada | 7.88718°N | 98.42319°E |
| 4 | Kathu | 7.89356°N | 98.35164°E |

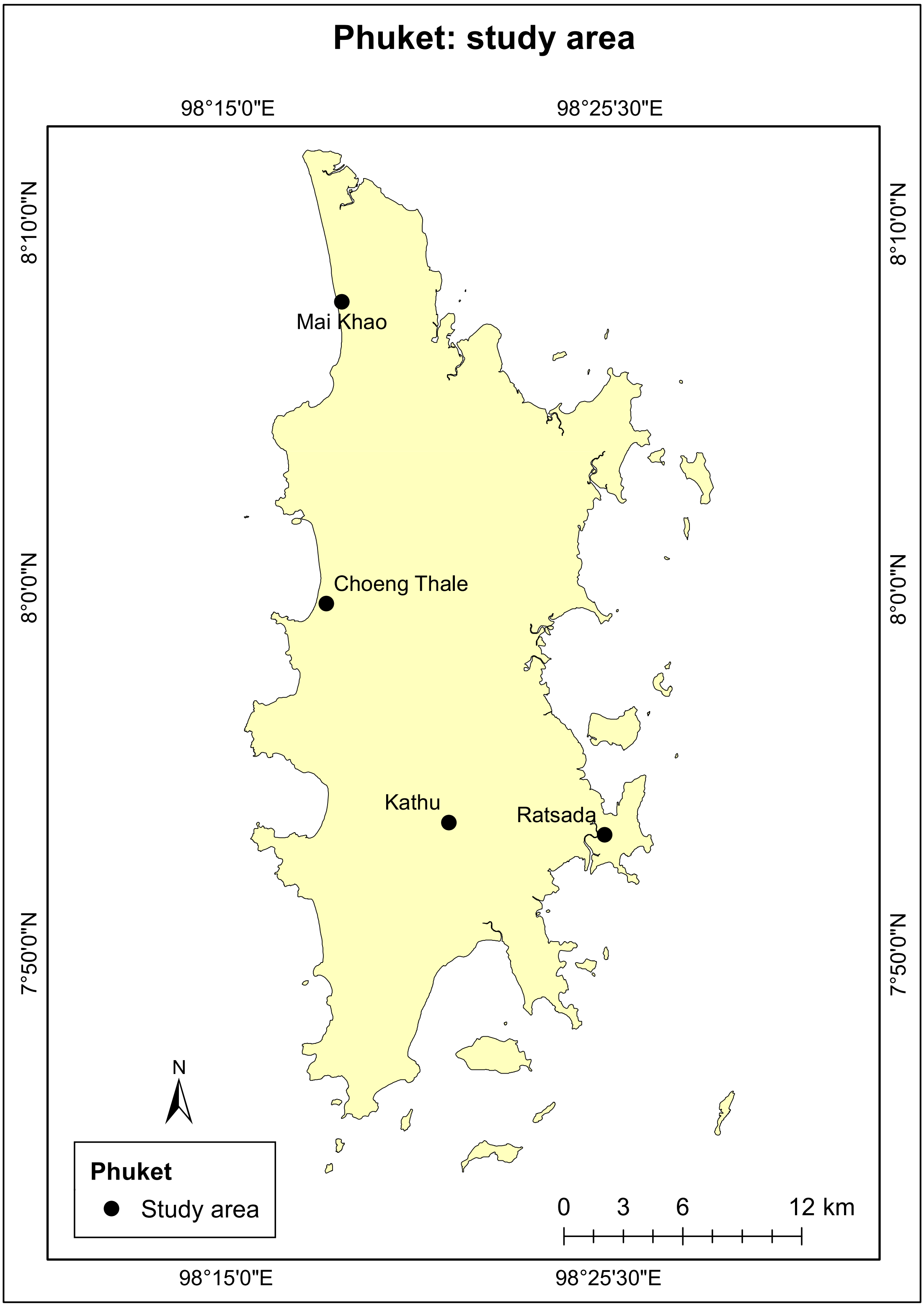


Figure 3.2 Map of the study area in Phuket

### 3.1.1 Geological Setting

Phuket is the largest island in Thailand and is well known for being surrounded by beaches. There is approximately 70% of this island that is covered by mountains, from the northern part to the southern part (440km), and 30% is a flat plain area lying in the central and eastern parts. It is described as the highest point of the island at 529 meters above the mean sea level (MASL) as the highest point on the island (Chanyotha et al., 2011). As shown in Figure 3.3.

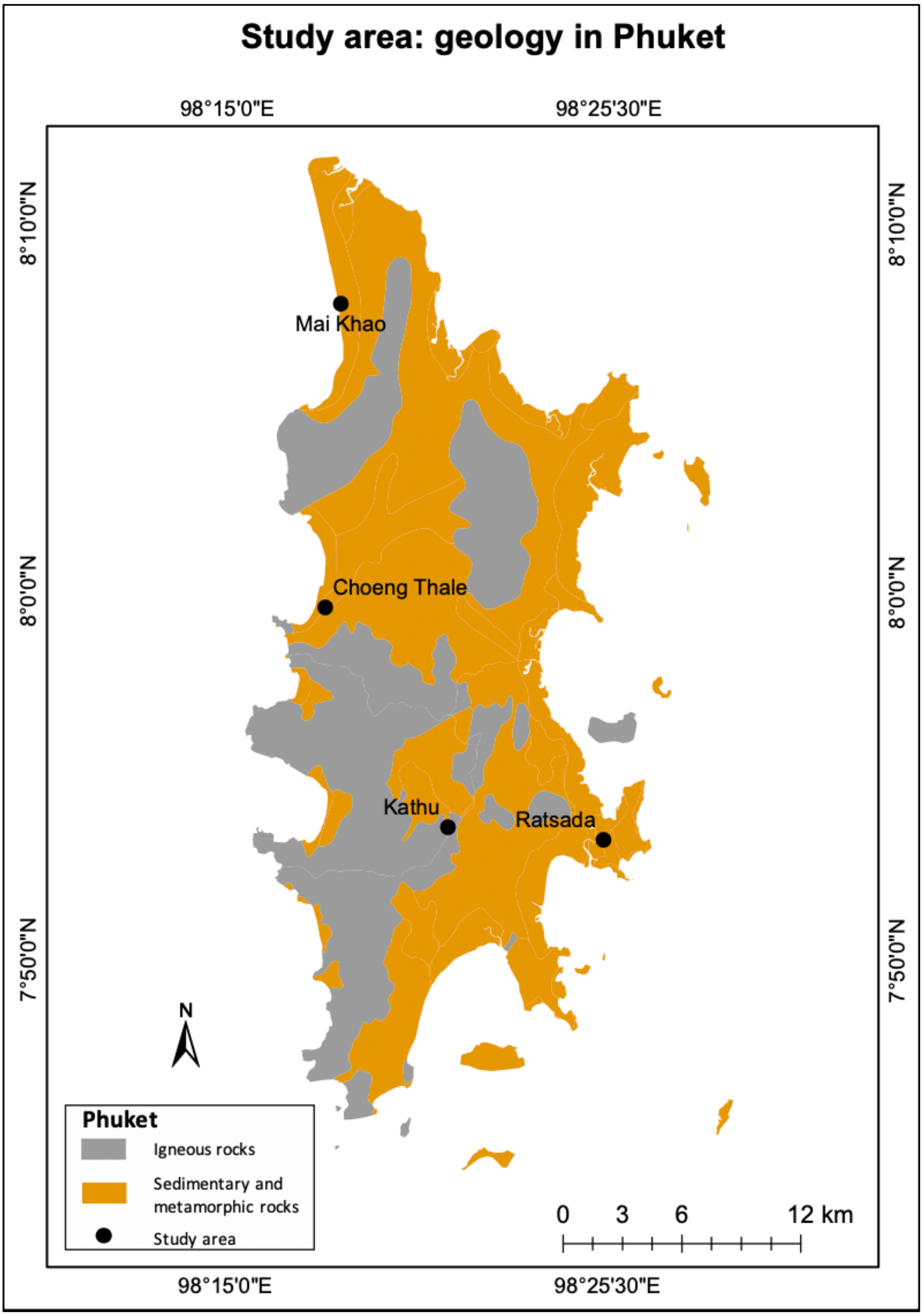


Figure 3.3 Map of geology in Phuket (DMR, 2007)

There are two different geological areas: (1) sedimentary and metamorphic rocks and (2) igneous rocks (DMR, 2007). Phuket Island is composed of sedimentary, metamorphic, and igneous rocks as alluvial deposits and bedrock (Brown et al., 1951). The sedimentary rocks are the oldest rocks on Phuket Island, which cover less than one-third of the island and outcrop in narrow strips along the east coast and adjacent small islands. They are clastic sediment, including mudstones (pebbly mudstones and laminated mudstones), siltstones, shales, and greywackes of Carboniferous to lower Permian age (DMR, 1989).

The granitic rocks are under the igneous rocks, which cover more than two-thirds of Phuket Island and outcrop mostly in the western and eastern central parts. Igneous rocks, such as pegmatites, aplite, and quartz veins, are widely distributed. They are most commonly found on the west coast and in central Phuket Island (DMR, 1989).

The metamorphic rocks of Phuket Island are relevant to granite emplacement and display parallelism of relic bedding and schistosity at a few places near the granite contact, whereas away from the contact they crosscut, as in the isolated sedimentary rocks around the east coast of Phuket Island. Some rocks have undergone very low-grade regional metamorphism. The highest-grade medium-to-coarse-grained metasedimentary rocks appear around the Kathu district (Tha Rau Mining). They maintain some distinctive sedimentary features, such as well-defined relict bedding and elongated or ellipsoid clasts or pebbles. The common rock types are mica-quartz schist, muscovite-quartz schist, quartz-mica hornfels, tremolite-actinolite quartzite and their less metamorphosed sedimentary equivalents (DMR, 1989).

3.1.2 Hydrogeology

The general climatic conditions in a tropical region like Thailand are under the influence of monsoon winds of seasonal character, such as the southwest monsoon and northeast monsoon. The southwest monsoon, which begins in May and brings a stream of warm, moist air towards Thailand from the Indian Ocean, Also, the Inter-Tropical Convergence Zone (ITCZ) and tropical cyclones cause rainfall in large amounts; May is a period when the ITCZ arrives in the south of Thailand. This southwest monsoon moves quickly northward and covers southern China from late June to early July. The ITCZ then reverses direction, passing over northern and northeastern

Thailand in August and central and southern Thailand in September and October. Additionally, the northeast monsoon begins in October and brings the cold and dry air from an anticyclone on the mainland of China over Thailand; the major parts are in the northern and northeastern higher latitude parts. In the south of Thailand, this northeast monsoon produces mild weather and abundant rain along the eastern coast of the country (Thai Meteorological Department, 2015).

According to a monsoonal climate feature, it is divided into two main seasons. The southwest monsoon dominates the rainy season, while the northeast monsoon dominates the dry season (Mayakun et al., 2010). The transitional period from the northeast to southwest monsoons is from mid-February to mid-May. April is the hottest month of the year.

Based on monthly rainfall distribution in Phuket, September reaches the highest point of approximately 380mm, and February is the lowest point of around 35mm. Even though April is the hottest month of the year, the amount of rainfall is still 150mm. Considering the average rainfall in Phuket in the last two decades, the level of rainfall of 190mm is counted as the rainy season, which is from May to November. While the level is lower than 190mm, that is the dry season, from December to April. The amount of monthly rainfall distribution from 1997 to 2017 is given in Figure 3.4, (Thai Meteorological Department, 2019).

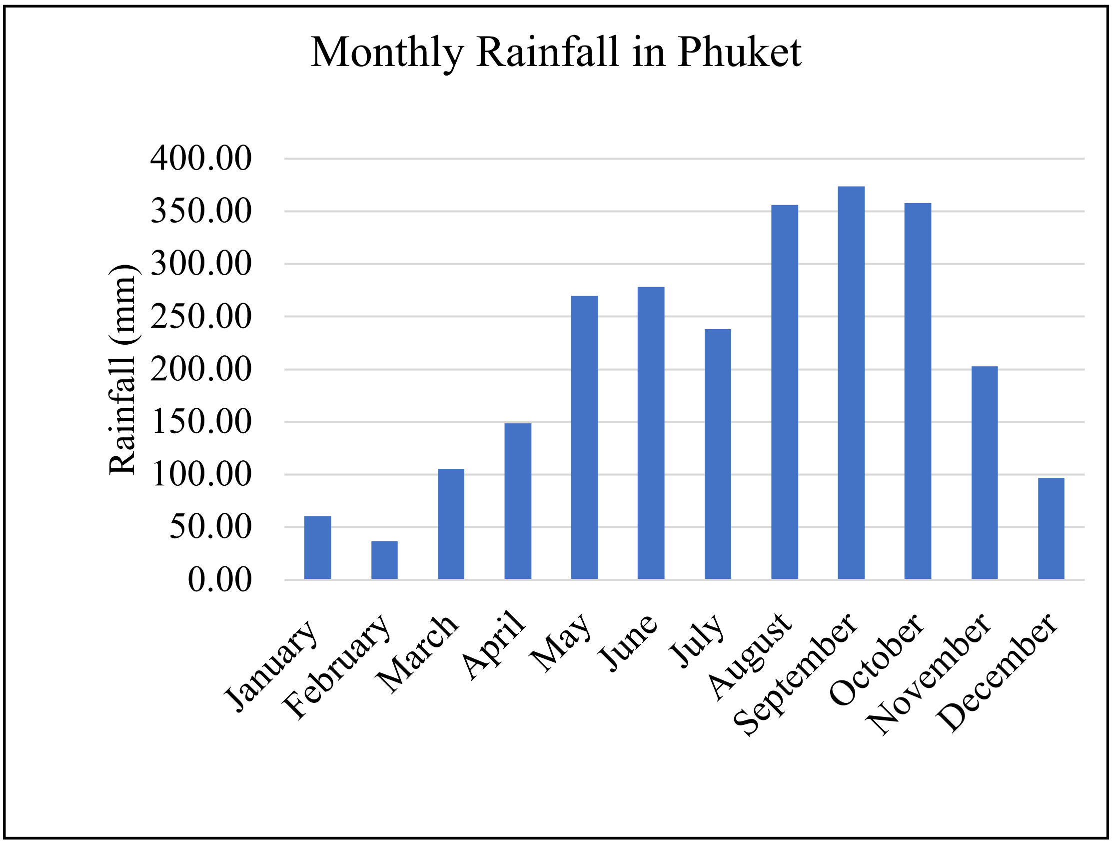


Figure 3.4 Average of monthly rainfall in Phuket from 1997 to 2017 (Thai Meteorological Department, 2019)

### 3.2 Research Methodology Description

This study focused mainly on geotechnical parameter estimations from standard penetration test (SPT) data and electrical resistivity data in Phuket, Thailand. Based on quantitative data from SPT, vertical electric sounding (VES) was employed around the SPT locations. Also, the depth of investigation was determined by the depth of SPT at study sites. The flow chart of the research methodology is given in Figure 3.5.

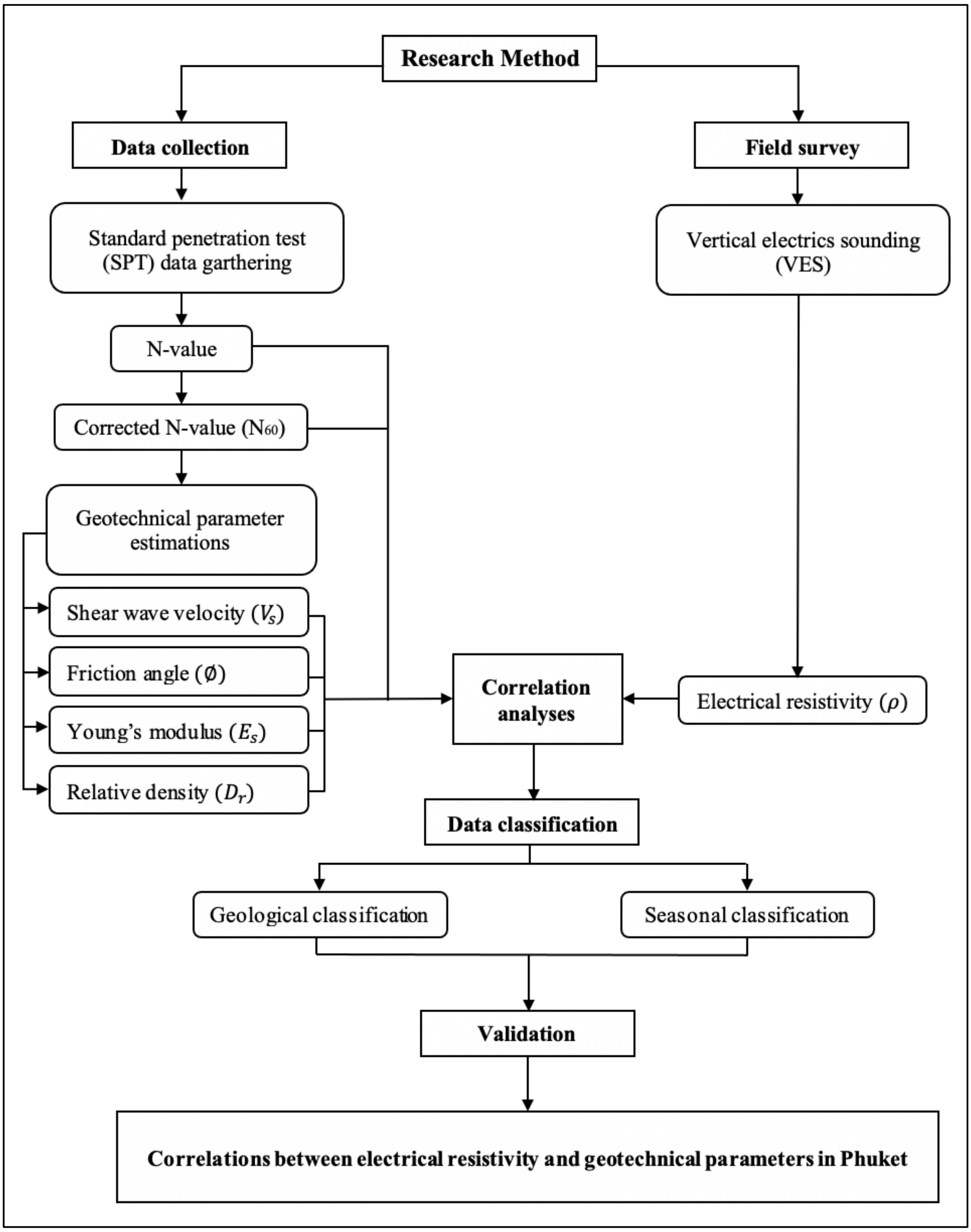


Figure 3.5 Flow chart of research methodology

### 3.3 Data Collection

SPT data for estimating soil strength at site investigation were obtained in Phuket, and SPT was performed in four different locations.Those included Mai Khao, Choeng Thale, Ratsada, and Kathu, which represent SPT-1, SPT-2, SPT-3, and SPT-4, respectively. Table 3.2 presents the locations of SPT in each study area. Geotechnical engineering reports include data for the SPT N-value with respect to depth.The reports provide information, i.e., location of the SPT station, borehole ID, depth, and N-value.

The grade total SPT data points were 84 in four different study areas. There were a total of 41 in Mai Khao, 5 in Choeng Thale, 20 in Ratsada, and 18 in Kathu. Table 3.3 shows the details of the SPT data.

Table 3.2 The locations of study area and SPT station in Phuket

| No. Location | Study Area | SPT Station |
|---|---|---|
| 1 | Mai Khao | SPT-1 |
| 2 | Choeng Thale | SPT-2 |
| 3 | Ratsada | SPT-3 |
| 4 | Kathu | SPT-4 |

Table 3.3 SPT data for estimating soil strength at site investigation in Phuket

| **No. Station** | **SPT** | **Borehole (BH)** | **Max. Depth (m)** | **Number of Data** | | |
|---|---|---|---|---|---|---|
| 1 | SPT-1 | BH-1 | 26.00 | 14 | 41 | 84 |
| | | BH-2 | 24.50 | 13 | | |
| | | BH-3 | 24.50 | 14 | | |
| 2 | SPT-2 | BH-1 | 23.00 | 5 | 5 | |
| 3 | SPT-3 | BH-1 | 5.00 | 4 | 20 | |
| | | BH-2 | 8.00 | 3 | | |
| | | BH-3 | 5.00 | 5 | | |
| | | BH-4 | 2.50 | 3 | | |
| | | BH-5 | 11.00 | 5 | | |
| 4 | SPT-4 | BH-1 | 5.50 | 6 | 18 | |
| | | BH-2 | 5.50 | 6 | | |
| | | BH-3 | 5.50 | 6 | | |

### 3.3.1 SPT N-value Correction ($\boldsymbol{N_{60}}$)

SPT N-value was corrected for the field procedure to receive the corrected N-value ($N_{60}$) for deriving other geotechnical parameters in this study such as shear wave velocity, friction angle, young's modulus, and relative density. The measurement of SPT N-value must be corrected (NovoSPT, 2021). The following SPT correction must be applied on N value to obtain $N_{60}$. The given Equation 2.1 was applied for calculating the $N_{60}$.

Where, $N$ is measured SPT N-value in the field. $N_{60}$ is corrected SPT N-value for field procedures. $C_E$ is energy level, adjust the SPT equipment energy to standard 60% energy (1.0). $C_B$ is borehole diameter correction, 65 – 115mm (1.0). $C_S$ is sampling method, standard sampler (1.0). $C_R$ is rod length correction, depend on the length of SPT rods (L) plus one meter typically; L < 4m (0.7); 4m < L < 6m (0.85); 6m < L < 10m (0.95); L > 10m (1.0).

### 3.4 Geotechnical Parameter Estimations

The variation of geotechnical parameters, including shear wave velocity $(V_s)$, friction angle $(\emptyset)$, Young's modulus $(E_s)$, and relative density $(D_r)$ in the subsurface with SPT data, which are available empirical correlations, suggested by different authors, has been used.

This study was focused on sandy soils as the location of the study area was in Phuket, which is an island. The following four equations below have been obtained from sandy soils (Bowles, 1996; Imai, 1977; Skempton, 1986; Terzaghi et al., 1996). Imai (1977), Terzaghi et al. (1996), Bowles (1996), and Skempton (1986) suggested Equations 3.1, 3.2, 3.3, and 3.4 for deriving $V_s, \emptyset$, $E_s$, and $D_r$, respectively. The common feature of these equations is using corrected N-value $(N_{60})$ for estimating $V_s$, $\emptyset$, $E_s$, and $D_r$, listed in the NovoSPT report (NovoSPT, 2020).

$$V_s = 80.6(N_{60})^{0.331} \tag{3.1}$$

$$\emptyset = 27 + (0.3N_{60})^{0.5} \tag{3.2}$$

$$E_s = \frac{6000N_{60}}{1000} \tag{3.3}$$

$$D_r = 12.4(N_{60})^{0.5} \tag{3.4}$$

### 3.5 Subsurface Investigation using Vertical Electric Sounding

Vertical electric sounding (VES) was implemented in this study due to its being a very attractive tool and simplicity for investigating the properties of subsurface and ground strata. As is widely known, an electrical resistivity survey is widely applied in engineering geological investigations of sites prior to construction, and then VES is a procedure that is employed in an electrical resistivity survey.

VES stations were deployed in various locations throughout Phuket, each of which corresponded to the location of the standard penetration test (SPT). As given in Table

3.4, the estimated depth for the VES survey used the approximated depth of SPT as a guideline in Mai Khao, Choeng Thale, Ratsada, and Kathu. For validating the data, Mai Khao and Choeng Thale were applied to two different VES stations. The total survey length could then be calculated in order to find a location with enough space for surveying. VES was carried out by using an AGI SuperSting R2 resistivity meter with an I electrode configuration. The I array, which was introduced (Kearey et al., 2002), is the most commonly used electrode configuration as it is simple and robust in which the current and potential electrodes are kept at equal spacing, and the spacing progressively increases from a fixed center. Then all four electrodes will be moved between successive readings.

The depth of investigations is carefully designed to be the same as the SPT data. Equations 2.4 and 2.5 were applied to estimate the depth for VES data as shown in Table 3.5. The VES data of the electrical resistivity survey was measured and recorded from the raw data, including depth of investigation, length, spacing, and apparent resistivity.

Table 3.4 The locations of study area and VES station in Phuket

| **No.** | **Study Area** | **VES Station** |
|---|---|---|
| 1 | Mai Khao | VES-1 |
| | | VES-1 (validation) |
| 2 | Choeng Thale | VES-2 |
| | | VES-2 (validation) |
| 3 | Ratsada | VES-3 |
| 4 | Kathu | VES-4 |

Table 3.5 Electrical resistivity survey using VES in Phuket

<table>
<tr><th>No. Station</th><th>VES</th><th>Max. depth $Z_e$ (m)</th><th>Max. length $L$ (m)</th><th>Max. spacing $a$ (m)</th><th>Array</th><th colspan="2">Number of Data</th></tr>
<tr><td>1</td><td>VES-1</td><td>26.00</td><td>150.30</td><td>50.10</td><td>Wenner</td><td>14</td><td rowspan="6">49</td></tr>
<tr><td>2</td><td>VES-2</td><td>23.00</td><td>132.96</td><td>44.32</td><td>Wenner</td><td>5</td></tr>
<tr><td>3</td><td>VES-3</td><td>11.00</td><td>63.59</td><td>21.20</td><td>Wenner</td><td>5</td></tr>
<tr><td>4</td><td>VES-4</td><td>5.50</td><td>31.80</td><td>10.60</td><td>Wenner</td><td>6</td></tr>
<tr><td>5</td><td>VES-1 (validation)</td><td>26.00</td><td>150.30</td><td>50.10</td><td>Wenner</td><td>14</td></tr>
<tr><td>6</td><td>VES-2 (validation)</td><td>23.00</td><td>132.96</td><td>44.32</td><td>Wenner</td><td>5</td></tr>
</table>

### 3.6 Correlation Analyses

The purpose of correlation analysis is to measure and interpret the strength of a linear or nonlinear relationship between two continuous variables. We then focus on the Pearson correlation coefficient. As with most of the previous work on electrical resistivity and geotechnical parameters, it has been done by using the Pearson correlation (Devi et al., 2017; Hatta & Syed Osman, 2015; Jusoh & Osman, 2017). Some of them have been done by applying the Spearman Rank analysis (Lin et al., 2017).

As the correlation coefficients take a range of values between -1 and +1, a value of 0 is uncorrelated between the two variables. A value greater than 0 indicates a positive correlation, as the value of one variable increases and the value of another variable also increases. A value less than 0 is a negative correlation as the value of one variable increases and the value of the other variable decreases.

When a correlation coefficient is equivalent to $-1$, it implies the data pairs have a perfect negative correlation. The correlation coefficient is closer to $-1$ indicates that negative correlation. The negative correlation coefficient shows a negative relationship between two variables as the value of one variable increases with the decreasing of the value of the other variable. When the correlation coefficient is equivalent to +1, it implies the data pairs have a perfect positive correlation. The correlation coefficient is closer to +1 indicates that positive correlation. The positive correlation coefficient shows a positive relationship between two variables as the value of one variable increases, while the value of the other variable is rising. When the correlation coefficient is equivalent to 0, it implies the data pairs have no correlation.

Table 3.6 Interpretation of correlation coefficient (Dancey & Reidy, 2007)

| **Value of Correlation Coefficient** | **Direction and Strength of Correlation** |
|---|---|
| -1.0 | Perfect negative |
| -0.7 to <-1.0 | Strong negative |
| -0.4 to <-0.7 | Moderate negative |
| -0.1 to <-0.4 | Weak negative |
| 0.0 | No correlation |
| 0.1 to <0.4 | Weak positive |
| 0.4 to <0.7 | Moderate positive |
| 0.7 to <1.0 | Strong positive |
| 1.0 | Perfect positive |

Following the guideline to interpreting the correlation coefficient that is given in Table 3.6. The sign of the correlation coefficient either positive or negative that expresses the direction of the relationship. The absolute value implies the strength of the correlation.

### 3.6.1 Pearson Analysis Method

The Pearson correlation coefficient is a measure of the strength and direction of a linear relationship between two variables (R. Peck et al., 2016). This Pearson correlation was introduced by Galton in 1877 and developed later by Karl Pearson in 1896, who was the first to describe the standard method of its calculation and to prove it to be the best one possible (Chee, 2015; Zou et al., 2003). The Pearson correlation coefficient establishes a relationship between two variables based on three assumptions, such as linear relationship, independent variables of each other, and distributed variables (Gogtay & Thatte, 2017). Then an important assumption is the normality of variables analyzed; this could be true only for quantitative variables (Hauke & Kossowski, 2011). It is a widely used correlation statistic to measure the degree of the linear relationship between two variables. For instance, the outcome variable changes linearly when the value of the predictor is manipulated, increased, or decreased. The following formula is used to compute the Pearson correlation coefficient:

$$r = \frac{N\sum xy-(\sum x)(\sum y)}{\sqrt{[N\sum x^2-(\sum x)^2][N\sum y^2 -(\sum y)^2]}} \tag{3.5}$$

Where, r is Pearson correlation coefficient, N is the number of data pair, ∑xy is the sum of data value, ∑x is the sum of x value, ∑y is the sum of y value, ∑x2 is the sum of squared x value, and ∑y2 is the sum of squared y value.

The advantage of using the Pearson correlation coefficient is that it is a simple method to indicate the presence or absence of correlation between two variables along with the degree to which they are correlated. This method can assess the direction of the correlation in which the correlation between variables is positive or negative. Through regression equations, this method is applicable to estimating the value of a dependent variable with reference to a particular value of an independent variable. However, this method has a limitation. The disadvantage of using the Pearson correlation coefficient is that it cannot identify relationships that are not linear**.** Then it may indicate a correlation of zero when the correlation has a relationship other than a linear relationship **(**Chee, 2015**).**

In the case where the data is correlated, it means the sum of the square of the difference between ranks will be small. The magnitude of the sum is relevant to the significance of the correlation. A result of the correlation coefficient is not just a result of chance. Thus, one approach to certifying the correlation coefficient is significance testing**.** A null hypothesis ($H_0$) is the starting point for any test's significance. According to it, sample observations are completely random. An alternative hypothesis $(H_a)$ is that sample observations are influenced by some non-random factor.

It is assumed that there is no correlation between the two variables in order to test the significance of the correlation. The probability of receiving a correlation coefficient is then determined. It is large or greater for a positive correlation and small or smaller for a negative correlation. It is accomplished by comparing the calculated value after modification to a table of critical values (Gauthier, 2001; Zar, 1972). If the absolute value of the calculated value is greater than the critical value, the correlation is significant. The $t$ statistic can also be calculated using the following equation. It is distributed as $t$ value with $n-2$ degrees of freedom, and it is a reasonable approximation. The hypothesis that the correlation coefficient is zero, and it can be calculated by calculating $t$ (Chee, 2015; Zar, 1972):

The Pearson correlation coefficient: $t = r\sqrt{\frac{(n-2)}{(1-r^2)}}$ **(3.6)**

Where r is the Pearson correlation coefficient**.** n is the sample size of paired scores. $df$ *is* $n-2$.

3.6.2 Least Squares Method

The least squares method is a form of mathematical regression analysis. It allows the analyst to determine the "best fit" for a set of data by various model functions or sets of equations. It was discovered by Carl Friedrich Gauss in 1795. This method is widely applied to creating scatter plots to visualize and interpret relationships between the data. The relationship between the independent variable and the dependent variable is represented by each data point. In regression analysis, the independent variable is illustrated on the horizontal axis (x). While the dependent variable is illustrated on the vertical axis (y). Depending on the residuals, least squares issues are divided into two categories: linear and non-linear. In statistical regression, the linear least squares problem is solved in closed form. Non-linear least squares problems, on the other hand, do not have a closed solution and are typically solved through iteration.

### 3.7 Data Classification

The selected data for sandy soils in Phuket was required. The data for this study was then divided into two major effecting parameters.That included the effect of geology and seasoning. These parameters are believed to be controlling factors in the relationship between the resistivity value of VES and geotechnical data. The parameters, i.e., geology and season, are considered for data correlation analysis. The effects of these parameters were analyzed and interpreted as follows: There are four different stations of SPT and VES that were conducted in the study area of Phuket, shown in Table 3.7. There are 84 data pairs for all the stations that are applicable for correlation analyses.

Table 3.7 For Phuket, four different stations of SPT and VES

| No. Station | SPT | VES | Geology | Season | |
|---|---|---|---|---|---|
| | | | | SPT | VES |
| 1 | SPT-1 | VES-1 | Sedimentary and metamorphic rocks | Rainy | Dry |
| 2 | SPT-2 | VES-2 | Sedimentary and metamorphic rocks | Rainy | Dry |
| 3 | SPT-3 | VES-3 | Sedimentary and metamorphic rocks | Dry | Dry |
| 4 | SPT-4 | VES-4 | Igneous rocks | Dry | Dry |

3.7.1 Geological Classification

Geologically, Phuket consists of sedimentary, metamorphic, and igneous rocks as alluvial deposits and bedrock (Brown et al., 1951). Granitic rock is the igneous rock that mainly covers more than two-thirds of Phuket Island. While sedimentary rock of Phuket group is the oldest rock of Phuket Island that covers less than one-third of the area in Phuket. Some rock of the Phuket group then has undergone very low-grade regional metamorphism.

Due to a change of resistivity can be affected by amounts of the contained water and the salinity of the common rocks. Igneous and metamorphic rocks have high resistivity values in general (Loke, 2015). They are highly influenced by the degree of fracturing and the proportion of cracks filled with groundwater (Loke, 2015). Depending on whether the rock is wet or dry, the range in resistivity for a given rock type is considerable, ranging from 1000 to 10 million Ωm (Loke, 2015). This property is useful for detecting fracture zones and other weathering features in engineering and groundwater surveys (Loke, 2015). In contrast to igneous and metamorphic rocks, sedimentary rock is more permeable and has a higher water content (Loke, 2015). In comparison to igneous and metamorphic rocks, sedimentary rocks have a low resistivity value. The resistivity range of sedimentary rock is approximately from 10 to10000 Ωm, and the most case is below 1000 Ωm (Loke, 2015). Consequently, the resistivity data and geotechnical data were classified into two types of geological rocks. One, the stiffness geology is igneous and metamorphic rocks. Two, the soft geology is sedimentary rocks for a geological factor of the correlation analysis.

There are four different stations of SPT and VES were separated into two geology groups, consisting sedimentary and metamorphic rocks and igneous rocks. Igneous rocks are available only one station. Thus, we consider about the sedimentary and metamorphic rocks, which are three different stations, is a main study for geological classification, as shown in Table 3.8. This study focused on the majority of the data on sedimentary and metamorphic rocks.

Table 3.8 Classification of sedimentary between SPT and VES

| **No. Station** | **SPT** | **VES** | **Geology** |
|---|---|---|---|
| 1 | SPT-1 | VES-1 | Sedimentary and metamorphic rocks |
| 2 | SPT-2 | VES-2 | Sedimentary and metamorphic rocks |
| 3 | SPT-3 | VES-3 | Sedimentary and metamorphic rocks |

3.7.2 Seasonal Classification

Generally, humid tropical zone like Phuket Island experience high rainfall areas with long periods of high temperatures (Saunders & Fookes, 1970). Consequently, the weathering process is much more progressive and causes an inconsistent present of water content (Tan et al., 2018). Also, a resistivity survey can predict the groundwater, which is identified as a lower resistivity zone and illustrates a change in resistivity value with depth. Normally, a low resistivity value is represented as a highly conductive zone that reflects a weak zone and vice versa.

The resistivity value can be affected by the degree of water the same as the N-value of SPT and other geotechnical parameters. As a result, the data were divided into two main seasons, rainy and dry, for correlation analyses. The rainy season is from May to November, dominated by the southwest monsoon, while the dry season is from December to April. It is based on the level of average monthly rainfall in Phuket, which is given in Figure 3.4.

Based on sedimentary and metamorphic rocks, there are divided into two seasonal groups, i.e., different seasons and the same seasons between SPT and VES employments. Thus, there are 20 data pairs only from Ratsada for the same seasons of seasonal classifications on sedimentary and metamorphic rocks, as shown in Table 3.9.

Table 3.9 Classification of sedimentary with same season between SPT and VES

| No. Station | SPT | VES | Geology | Season | |
|---|---|---|---|---|---|
| | | | | SPT | VES |
| 1 | SPT-3 | VES-3 | Sedimentary and metamorphic rocks | Dry | Dry |

## 3.8 Validation

To establish the relationship between electrical resistivity and geotechnical factors, a data validation procedure was used to ensure data accuracy. In Phuket, geology and seasoning play a role. For validation, the ERM was re-run in the rainy season at stations 1 and 2. Thus, there are 66 data pairs for the validation dataset as the same as the geology and season were used to do a cross plot again.

VES validation for sedimentary and metamorphic rocks, VES-1 (validation) and VES-2 (validation), were conducted in the rainy season. VES-1 (validation) and VES-2 (validation) would be used to correlate with SPT-1 and SPT-2, which were done in the rainy season, respectively. Thus, the location of the validation of data is given in Table 3.10.

Table 3.10 Validation of sedimentary with same season between SPT and VES

| **No. Station** | **SPT** | **VES** | **Geology** | **Season** | |
|---|---|---|---|---|---|
| | | | | **SPT** | **VES** |
| 1 | SPT-1 | VES-1 (validation) | Sedimentary and metamorphic rocks | Rainy | Rainy |
| 2 | SPT-2 | VES-2 (validation) | Sedimentary and metamorphic rocks | Rainy | Rainy |
| 3 | SPT-3 | VES-3 | Sedimentary and metamorphic rocks | Dry | Dry |

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 The Relationship between Electrical Resistivity and Geotechnical Parameters

### 4.1.1 Electrical Resistivity vs. N-value and $N_{60}$

Table 4.1 All data: the relationship of electrical resistivity with N-value and $N_{60}$ for sand layers in Phuket

| **Dataset (All data)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 | SPT-1 | $N$ | 0.0027 | 0.0247 | 0.9804 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-4 | SPT-4 | | | | |
| VES-1 | SPT-1 | $N_{60}$ | -0.0134 | -0.1213 | 0.9038 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-4 | SPT-4 | | | | |

Table 4.1 showcases the Pearson coefficient $(r)$ of electrical resistivity with geotechnical parameters for all data of sand layers in Phuket. There was no correlation and no significant relationship of electrical resistivity with N-value and $N_{60}$. The $r$ value between electrical resistivity and N-value was 0.0027 for all data, as shown in Table 4.1. It demonstrates that there was no statistically significant relationship between electrical resistivity and N-value. Since the t-distribution for testing hull

hypothesis was found to equal 0.0247, the p-value was equal 0.9804, greater than 0.05. Hence, the null hypothesis was supported. Similarly, for all data, there was no correlation and no significant relationship between electrical resistivity and N-value.

The $r$ value between electrical resistivity and $N_{60}$ was -0.0134 for all data, as given in Table 4.1. It reveals that there was no significant relationship between electrical resistivity and $N_{60}$. Since the t-distribution for testing hull hypothesis was found to equal -0.1213, the p-value was equal 0.9038, greater than 0.05, and the null hypothesis was not rejected. Thus, for all data, electrical resistivity had no association and significant relationship with $N_{60}$.

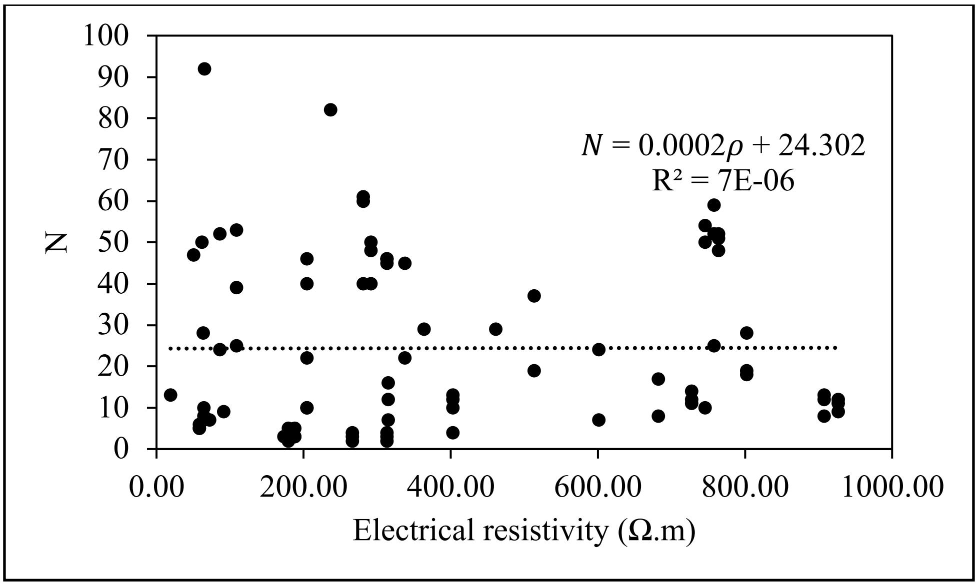


Figure 4.1 All data: relationship between electrical resistivity and N-value

Figure 4.1 depicts a relationship between electrical resistivity and N-value for all data. The linear regression represented the functional relationship of electrical resistivity with N-value. The trend of electrical resistivity with N-value was discovered to have no shape as the data points on the corresponding graph would approximate a circle. The $R^2$ value for the relationship between electrical resistivity and N-value was 7E-06 ($R^2 = 0.000007$). As a result, there was no relationship of electrical resistivity with N-value for all data.

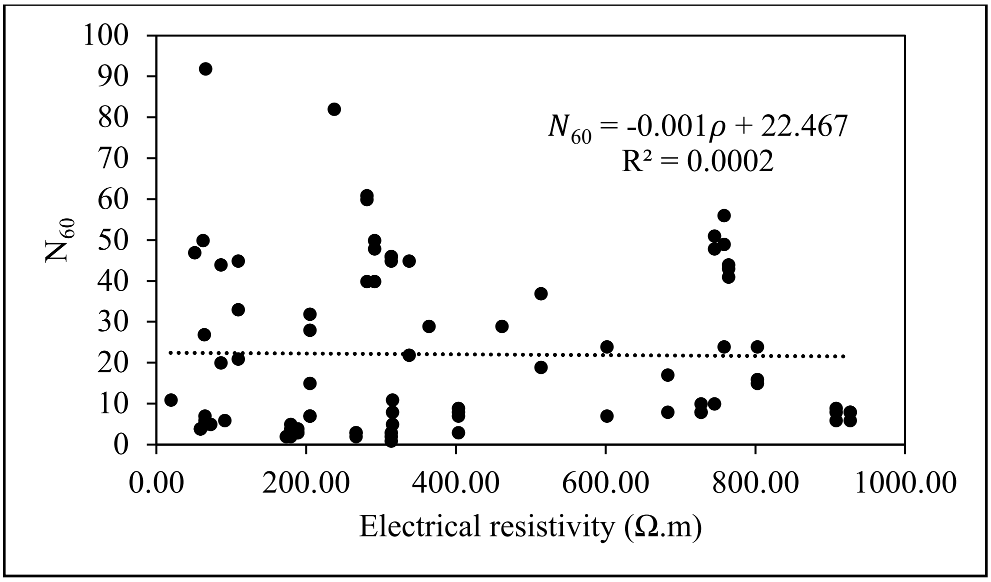


Figure 4.2 All data: relationship between electrical resistivity and $N_{60}$

Figure 4.2 views a relationship between electrical resistivity and $N_{60}$ for all data. The functional relationship of electrical resistivity with $N_{60}$ was represented by linear regression. The trend of electrical resistivity and $N_{60}$ was not found due the data points on the corresponding graph would approximate a circle. The $R^2$ value was 0.0002 for the relationship between electrical resistivity and $N_{60}$. Thus, electrical resistivity was not correlated with $N_{60}$ for all data.

4.1.2 Electrical Resistivity vs. Shear Wave Velocity

Table 4.2 All data: the relationship of electrical resistivity with shear wave velocity for sand layers in Phuket

| **Dataset (All data)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-1 | SPT-1 | $V_s$ | 0.0676 | 0.6136 | 0.5412 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-4 | SPT-4 | | | | |

The $r$ value between electrical resistivity and shear wave velocity was 0.0676 for all data, as presented in Table 4.2. It proves that there was no statistically significant relationship between electrical resistivity and shear wave velocity. The p-value was equal 0.5412, larger than 0.05, because the t-distribution for testing hull hypothesis was found to equal 0.6136. Thus, the null hypothesis was proved. This shows there was no correlation and significant relationship between electrical resistivity and shear wave velocity for all data.

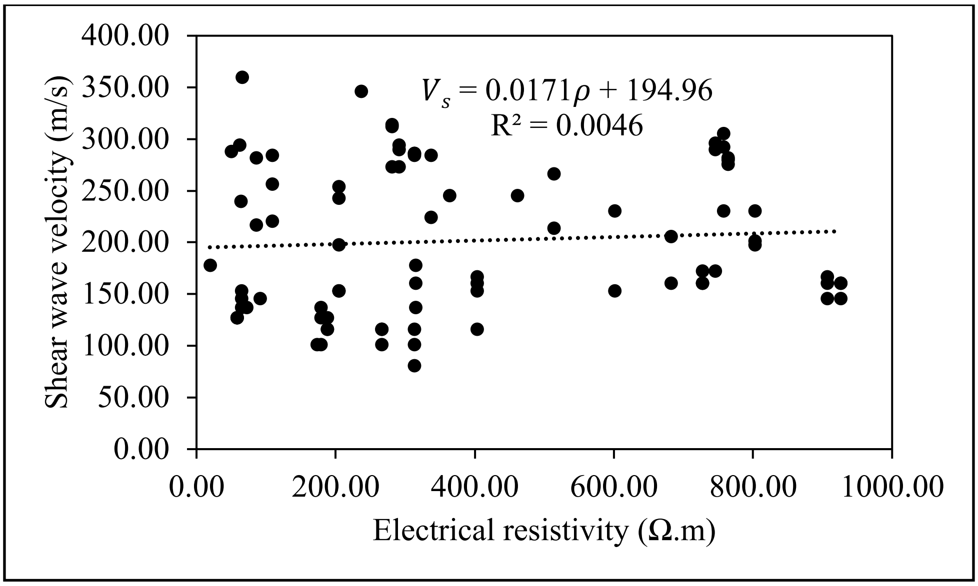


Figure 4.3 All data: relationship between electrical resistivity and shear wave velocity

Figure 4.3 views a relationship between electrical resistivity and shear wave velocity for all data. The linear function was used to describe the functional relationship between electrical resistivity and shear wave velocity. It was revealed that there was no trend between electrical resistivity and shear wave velocity since the data points on the corresponding graph would approximate a circle. The value of $R^2$ was 0.0046 for the relationship of electrical resistivity with shear wave velocity. Consequently, for all data, there was no relationship between electrical resistivity and shear wave velocity.

4.1.3 Electrical Resistivity vs. Friction Angle

Table 4.3 All data: the relationship of electrical resistivity with friction angle for sand layers in Phuket

| **Dataset (All data)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 | SPT-1 | ∅ | -0.0134 | -0.1213 | 0.9038 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-4 | SPT-4 | | | | |

As shown in Table 4.3, the $r$ value between electrical resistivity and friction angle for all data was -0.0134. It reveals that there is no statistically significant relationship between electrical resistivity and friction angle. The p-value was equal 0.9038, exceeded 0.05 since the t-distribution for testing hull hypothesis was found to equal -0.1213. Hence, the null hypothesis was not rejected. Correspondingly, the relationship between electrical resistivity and friction angle was not correlated and significant for all data.

Figure 4.4 below portrays a relationship between electrical resistivity and friction angle for all data. The functional relationship between electrical resistivity and friction angle was determined using linear regression. It was noticed that there was no direction of electrical resistivity with friction angle because the data points on the corresponding graph would approximate a circle. The $R^2$ value for the relationship between electrical resistivity and friction angle was 0.0002. Subsequently, there was no relationship between electrical resistivity and friction angle for all data.

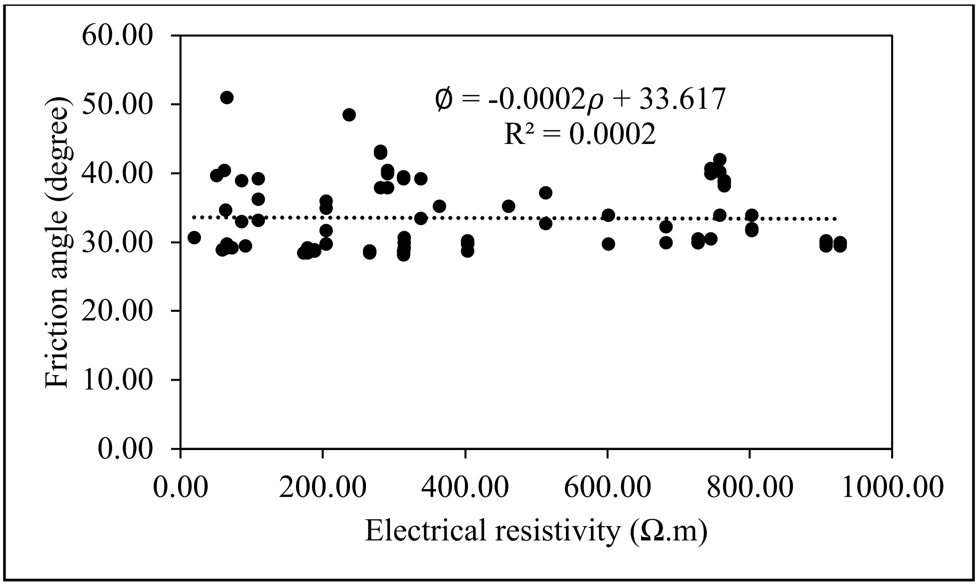


Figure 4.4 All data: relationship between electrical resistivity and friction angle

4.1.4 Electrical Resistivity vs. Young's Modulus

Table 4.4 All data: the relationship of electrical resistivity with Young's modulus for sand layers in Phuket

| **Dataset (All data)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 | SPT-1 | $E_s$ | -0.0134 | -0.1213 | 0.9038 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-4 | SPT-4 | | | | |

The $r$ value between electrical resistivity and Young's modulus for all data was -0.0134, as represented in Table 4.4. It has shown that there was no significant relationship between electrical resistivity and Young's modulus. The p-value was equal 0.9038, larger than 0.05 as the t-distribution for testing hull hypothesis was found to equal -0.1213; so, the null hypothesis was maintained. Similarly, for all data, electrical resistivity did not correlate with Young's modulus, and it had no significant.

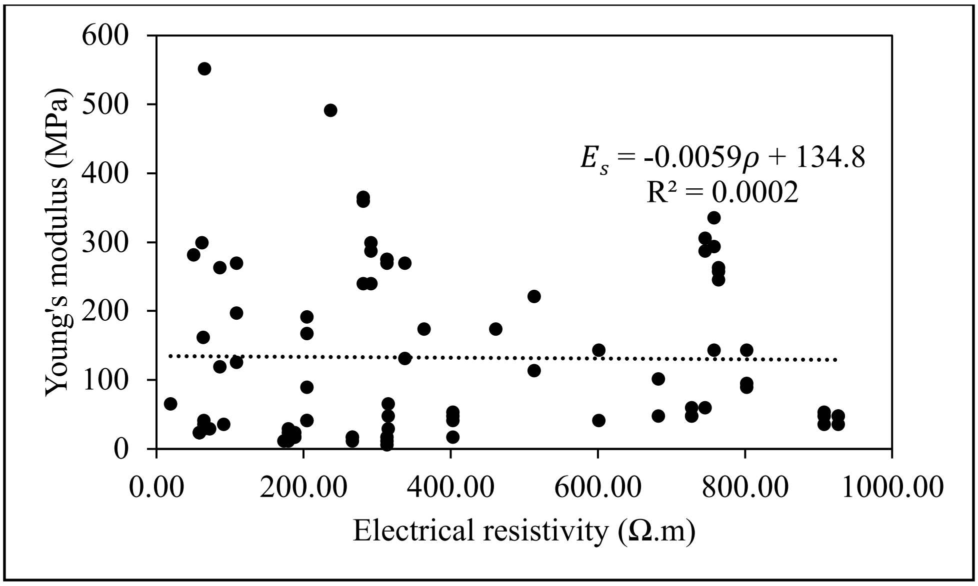


Figure 4.5 All data: relationship between electrical resistivity and Young's modulus

Figure 4.5 illustrations a relationship of electrical resistivity with Young's modulus for all data. Electrical resistivity had a linear relationship with Young's modulus. There had no direction of electrical resistivity with Young's modulus, while the data points on the corresponding graph would approximate a circle. The $R^2$ for the relationship of electrical resistivity with Young's modulus was 0.0002. Thus, for all data, there was no relationship of electrical resistivity with Young's modulus.

4.1.5 Electrical Resistivity vs. Relative Density

Table 4.5 All data: the relationship of electrical resistivity with relative density for sand layers in Phuket

| **Dataset (All data)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-1 | SPT-1 | $D_r$ | 0.0446 | 0.4043 | 0.6870 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-4 | SPT-4 | | | | |

The $r$ value between electrical resistivity and relative density was 0.0466 for all data, as can be seen in Table 4.5. It confirms that there was no significant relationship between electrical resistivity and relative density. As the t-distribution for testing hull hypothesis was found to equal 0.4043.The p-value was equal 0.6870, greater than 0.05. Therefore, the null hypothesis was not rejected. Equally, for all data, electrical resistivity was not correlated and significant relationship with relative density.

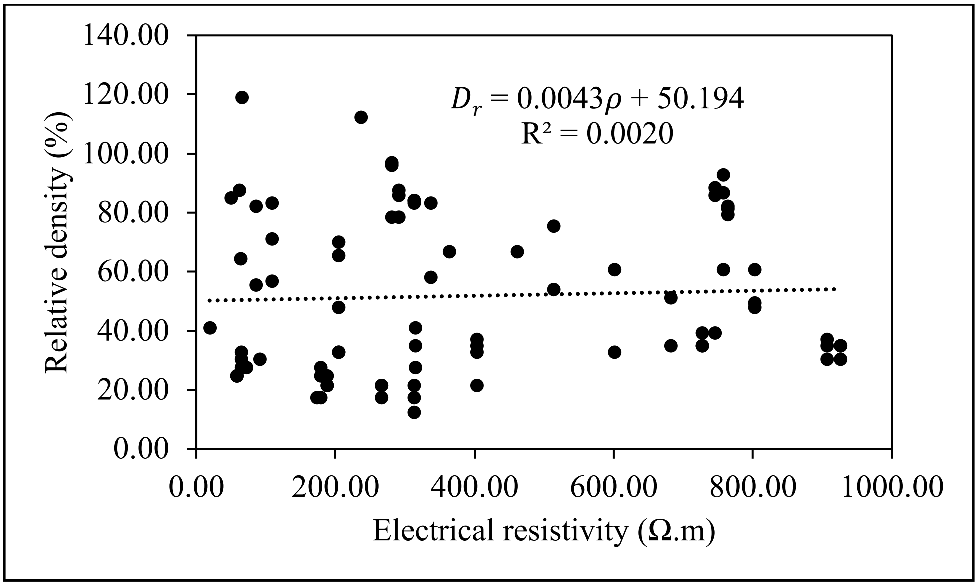


Figure 4.6 All data: relationship between electrical resistivity and relative density

Figure 4.6 describes a relationship between electrical resistivity and relative density for all data. The linear regression was used the functional relationship of electrical resistivity with relative density. The trend of electrical resistivity and relative density was not found due the data points on the corresponding graph would approximate a circle. The Value of $R^2$ for the relationship between electrical resistivity and relative density was 0.0020. Therefore, for all data, there was no relationship between electrical resistivity and relative density.

## 4.2 The Relationship between Electrical Resistivity and Geotechnical Parameters Based on Geological Classification

4.2.1 Electrical Resistivity vs. N-value and $N_{60}$

Table 4.6 Geological classification: the relationship of electrical resistivity with N-value and $N_{60}$ for sand layers in Phuket

| Dataset (Geological classification) | | Parameters | Pearson coefficient (r) | t-distribution | Significance (p-value) |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 | SPT-1 | $N$ | -0.2440* | -2.0129 | 0.0483 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-1 | SPT-1 | $N_{60}$ | -0.2464* | -2.0339 | 0.0461 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

*. Correlation is significant at the 0.05 level (2-tailed).

Table 4.6 presents the Pearson coefficient ($r$) of electrical resistivity with geotechnical parameters for geological classification of sand layers in Phuket. The relationship between electrical resistivity and N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density were weak, linear, and negative. There was a statistically significant relationship of electrical resistivity with N-value, $N_{60}$, friction angle, and young's modulus (p-value < 0.05), while the relationship of electrical resistivity with shear wave velocity and relative density was not given a significance (p-value > 0.05).

As shown in Table 4.6, the $r$ value between electrical resistivity and N-value for geological classification on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES was -0.2440. It reveals that an increase of electrical resistivity would lead to decrease N-value. As the t-distribution for testing hypothesis was found to equal -2.0129, the p-value was equal 0.0483. There was a significant relationship between electrical resistivity and N-value due the p-value was less than 0.05. Thus, the alternative hypothesis was supported. Similar manner, the relationship of electrical resistivity with N-value was shown to be weakly negative and statistically significant.

The $r$ value between electrical resistivity and $N_{60}$ for geological classification on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES was -0.2464, as shown in Table 4.6. It discloses that $N_{60}$ decreased with an increasing of electrical resistivity. Since the t-distribution for testing hypothesis was found to equal -2.0339, the p-value was equal 0.0461. The relationship of electrical resistivity and $N_{60}$ was a statistical significance. The p-value was less than 0.05, and the alternative hypothesis was not rejected. Similarly, electrical resistivity was found to have weakly negative and statistically significant relationship with $N_{60}$.

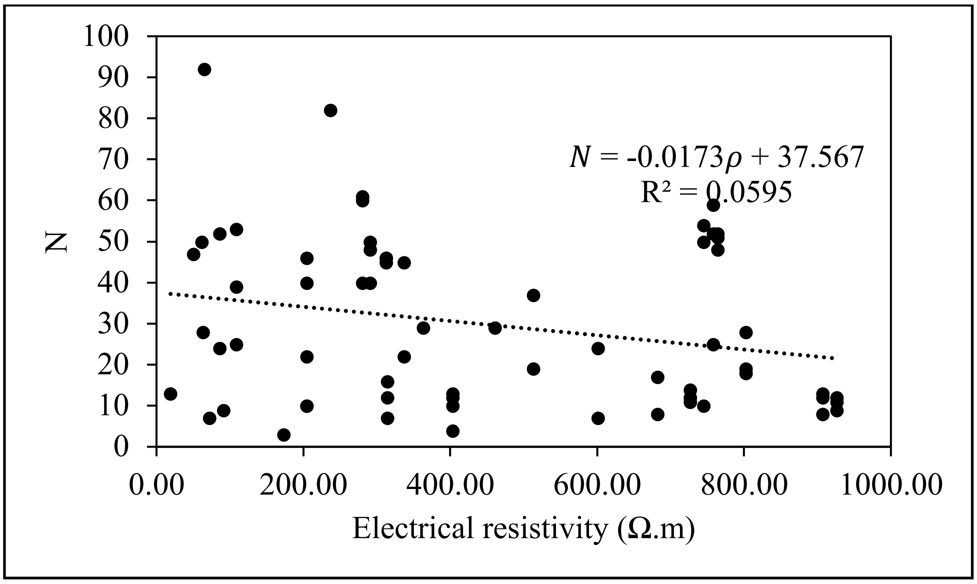


Figure 4.7 Geological classification: relationship between electrical resistivity and N-value on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES

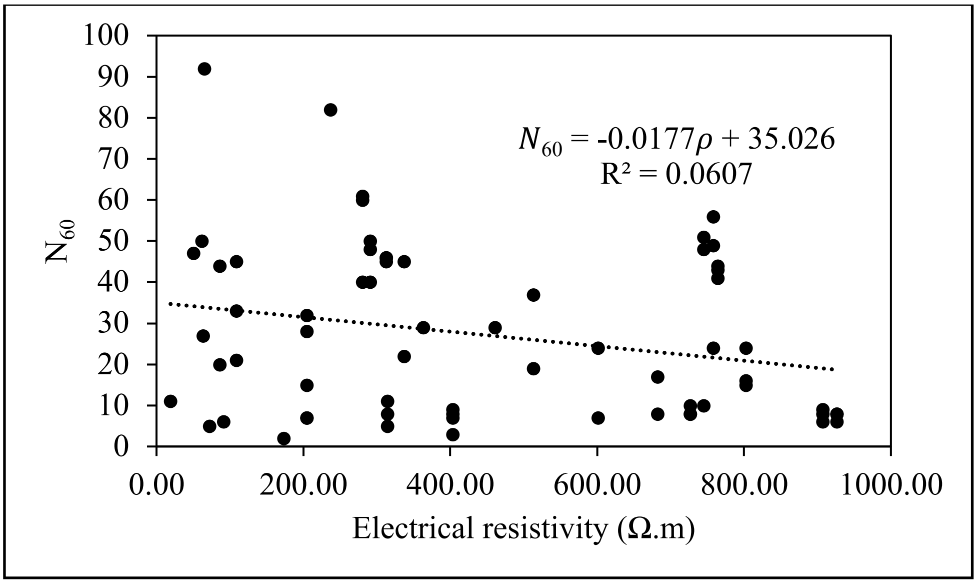


Figure 4.8 Geological classification: relationship between electrical resistivity and $N_{60}$ on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES

Figure 4.7 below shows a relationship between electrical resistivity and N-value for geological classification. Linear regression was used to explore the functional relationship between electrical resistivity and N-value. It was discovered that electrical resistivity with N-value had no trend as the data points on the corresponding graph were randomly scattered. The electrical resistivity and N-value relationship was $R^2$ at 0.0595. Therefore, for geological classification, there was no relationship between electrical resistivity and N-value.

Figure 4.8 below depicts a relationship between electrical resistivity and $N_{60}$ for geological classification. Linear regression was used to examine the functional relationship of electrical resistivity with $N_{60}$. It was discovered that the trend of electrical resistivity with $N_{60}$ was not found due to randomly scattered on the corresponding graph. The relationship between electrical resistivity and $N_{60}$, $R^2$ was at 0.0607. Therefore, there was no relationship between electrical resistivity and $N_{60}$ for geological classification.

4.2.2 Electrical Resistivity vs. Shear Wave Velocity

Table 4.7 Geological classification: the relationship of electrical resistivity with shear wave velocity for sand layers in Phuket

| **Dataset (Geological classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-1 | SPT-1 | $V_s$ | -0.2189 | -1.7951 | 0.0774 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

The $r$ value of electrical resistivity and shear wave velocity for geological classification on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES was -0.2189, as shown in Table 4.7. It bares that as electrical resistivity increased, shear wave velocity decreased. Since the t-distribution for testing hypothesis was found to equal -1.7951, the p-value was equal 0.0774. On the other hand, there was not statistically significant relationship between electrical resistivity and shear wave velocity, and the p-value exceeded 0.05. Therefore, the alternative hypothesis was rejected. Relatedly, the relationship between electrical resistivity and shear wave velocity was presented to be weakly negative and statistically insignificant.

Figure 4.9 below displays a relationship between electrical resistivity and shear wave velocity for geological classification. The functional relationship between electrical resistivity and shear wave velocity was using linear regression. It was discovered that the trend of electrical resistivity with shear wave velocity was not found due to randomly scattered data points. The relationship between electrical resistivity and shear wave velocity was $R^2$ at 0.0479. Thus, for geological classification, there was no relationship between electrical resistivity and shear wave velocity.

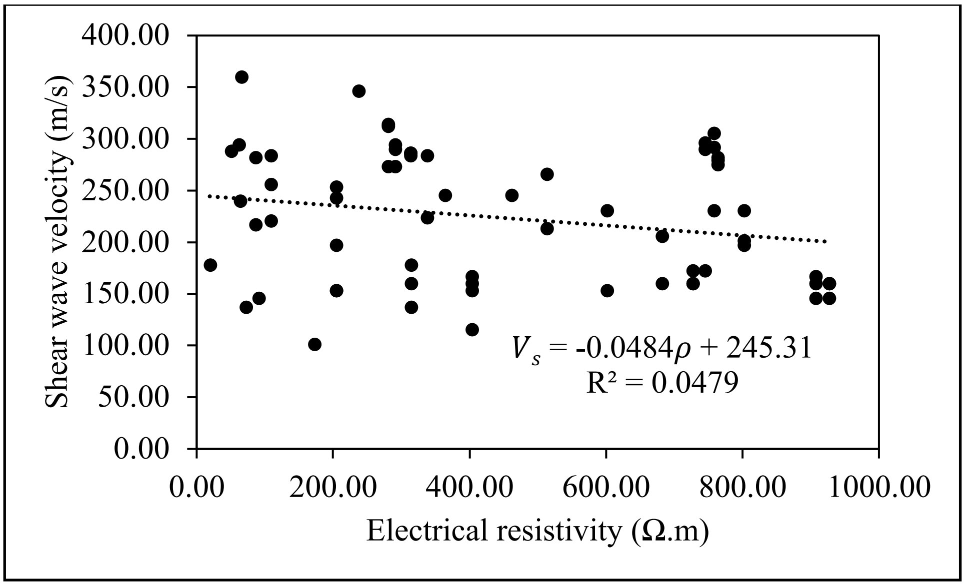


Figure 4.9 Geological classification: relationship between electrical resistivity and shear wave velocity on sedimentary and metamorphic rocks

4.2.3 Electrical Resistivity vs. Friction Angle

Table 4.8 Geological classification: the relationship of electrical resistivity with friction angle for sand layers in Phuket

| **Dataset (Geological classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | ***ρ*** | ***ρ*** | ***ρ*** |
| VES-1 | SPT-1 | ∅ | -0.2464* | -2.0339 | 0.0461 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

*. Correlation is significant at the 0.05 level (2-tailed).

The $r$ value between electrical resistivity and friction angle for geological classification on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES was -0.2464, as seen on Table 4.8. It exposes that as electrical resistivity increased, so did friction angle. Since the t-distribution for testing hypothesis was found to equal -2.0339, which significant with the p-value was equal

0.0461. There was a significant relationship between electrical resistivity and friction angle as the p-value became less than 0.05, and the alternative hypothesis was supported. Similarly, the relationship of electrical resistivity with friction angle was discovered to be weakly negative and statistically significant.

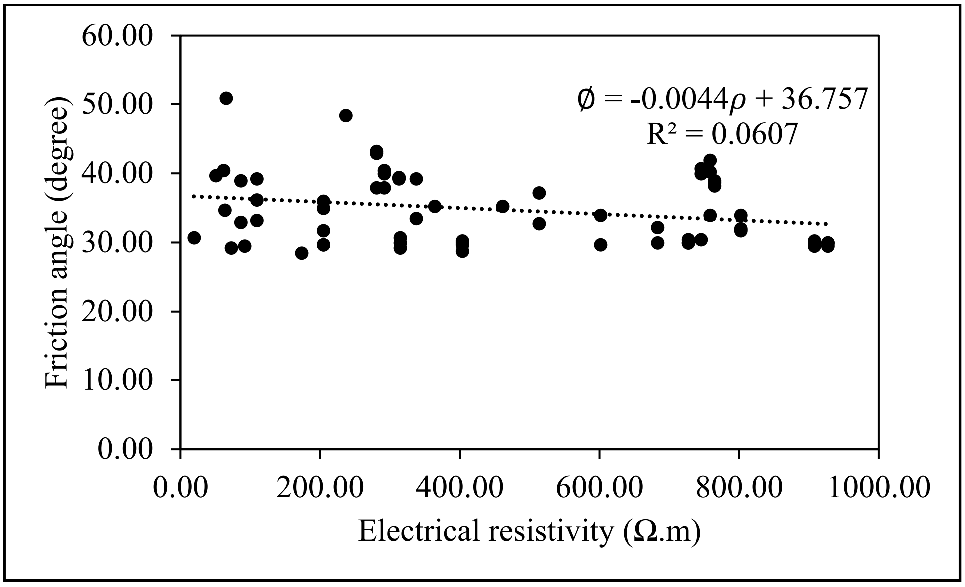


Figure 4.10 Geological classification: relationship between electrical resistivity and friction angle on sedimentary and metamorphic rocks

Figure 4.10 describes a relationship between electrical resistivity and friction angle for geological classification. Linear regression was used to determine the functional relationship between electrical resistivity and friction angle. It was not found the trend of electrical resistivity and friction angle because of random scattered data points. The $R^2$ value for the relationship between electrical resistivity and friction angle was 0.0607. Thus, there was no relationship between electrical resistivity and friction angle for geological classification.

4.2.4 Electrical Resistivity and Young's Modulus

Table 4.9 Geological classification: the relationship of electrical resistivity with Young's modulus for sand layers in Phuket

| **Dataset (Geological classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 | SPT-1 | $E_s$ | -0.2464* | -2.0339 | 0.0461 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

*. Correlation is significant at the 0.05 level (2-tailed).

The $r$ value between electrical resistivity and young's modulus for geological classification on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES was -0.2464, as shown in Table 4.9. It reveals that a decrease of young's modulus was accompanied by an increasing of electrical resistivity. As the t-distribution for testing hypothesis was discovered to equal -2.0339, which significant with the p-value was equal 0.0461. There was a significant relationship between electrical resistivity and Young's modulus. The p-value was less than 0.05; the alternative hypothesis was supported. Thus, the relationship of electrical resistivity with young's modulus was determined to be weakly negative and statistically significant.

Figure 4.11 below illustrates a relationship between electrical resistivity and Young's modulus for geological classification. Linear regression was used to investigate the functional relationship between electrical resistivity and young's modulus. It was not found the direction of electrical resistivity with young's modulus as the data points were randomly scattered on the corresponding graph. The $R^2$ value for the relationship between electrical resistivity and Young's modulus was 0.0607. As a result, for geological classification, there was no relationship between electrical resistivity and Young's modulus.

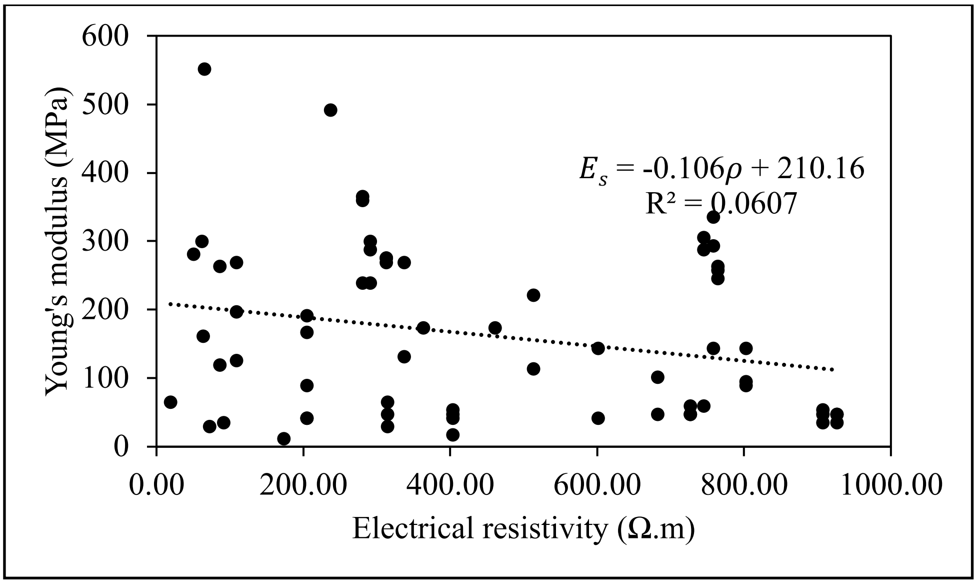


Figure 4.11 Geological classification: relationship between electrical resistivity and Young's modulus on sedimentary and metamorphic rocks

4.2.5 Electrical Resistivity vs. Relative Density

Table 4.10 Geological classification: the relationship of electrical resistivity with relative density for sand layers in Phuket

| **Dataset (Geological classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 | SPT-1 | $D_r$ | -0.2290 | -1.8819 | 0.0644 |
| VES-2 | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

The $r$ value between electrical resistivity and relative density for geological classification on sedimentary and metamorphic rocks and different seasons of employment for SPT and VES was -0.2290, as shown in Table 4.10. It demonstrates that relative density decreased while electrical resistivity increased. However, there was not statistically significant relationship between electrical resistivity and relative density. Since the t-distribution for testing hypothesis was found to equal -1.8819, which significant with the p-value was equal 0.0644. The p-value was greater than 0.05; the alternative hypothesis was not supported. As a result, for geological classification, the relationship between electrical resistivity relative density was to be weakly negative and statistically insignificant.

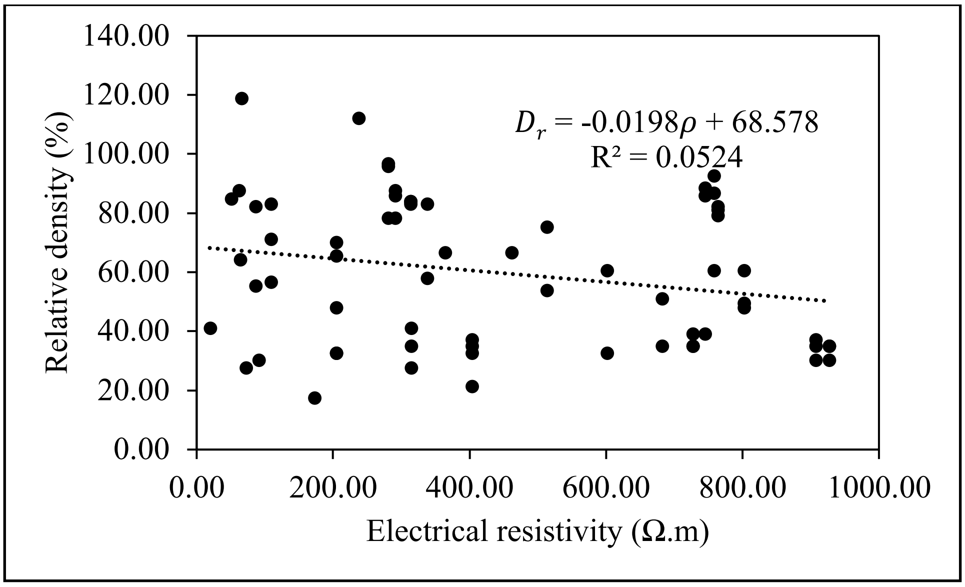


Figure 4.12 Geological classification: relationship between electrical resistivity and relative density on sedimentary and metamorphic rocks

Figure 4.12 mentions a relationship between electrical resistivity and relative density for geological classification. The functional relationship between electrical resistivity and relative density was represented by linear regression. It was demonstrated that the trend of electrical resistivity with relative density was not found, which was randomly scattered data points. The relationship between electrical resistivity and relative density was $R^2$ at 0.0524. As a result, there was no relationship between electrical resistivity and relative density for geological classification.

## 4.3 The Relationship between Electrical Resistivity and Geotechnical Parameters Based on Seasonal Classification

4.3.1 Electrical Resistivity vs. N-value and $N_{60}$

Table 4.11 Seasonal classification: the relationship of electrical resistivity with N-value and $N_{60}$ for sand layers in Phuket

| **Dataset (Seasonal classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-3 | SPT-3 | $N$ | -0.7012** | -4.1728 | 0.0006 |
| VES-3 | SPT-3 | $N_{60}$ | -0.7035** | -4.1996 | 0.0005 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

Table 4.11 represents the Pearson coefficient $(r)$ of electrical resistivity with geotechnical parameters for seasonal classification of sand layers in Phuket. The relationship between electrical resistivity and N-value, $N_{60}$, friction angle, Young's modulus, and relative density were strong, linear, and negative, while the relationship of electrical resistivity with shear wave velocity was very strong, linear, and negative. There was the statistically high significant relationship of electrical resistivity with N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density ($p$-value < 0.01).

The $r$ value between electrical resistivity and N-value for seasonal classification was -0.7012, as given in Table 4.11. It demonstrates that N-value decreased as electrical resistivity increased. Since the t-distribution for testing hypothesis was found to equal -4.1728, which significant with the p-value was equal 0.0006. Electrical resistivity and N-value had a high statistically significant relationship due the p-value was less than 0.01. The null hypothesis was rejected. Similarly, the relationship between electrical resistivity and N-value was found to have the strong negative and high significant.

As shown in Table 4.11, the $r$ value between electrical resistivity and $N_{60}$ for seasonal classification was -0.7035. It reveals that an increasing of electrical resistivity would lead to decrease $N_{60}$. Since the t-distribution for testing hypothesis was found to equal -4.1996, which significant with the p-value was equal 0.0005. There was the high significant relationship between electrical resistivity and $N_{60}$. The p-value was less than 0.01; thus, the null hypothesis was rejected. Similarly, there was found that electrical resistivity had the strong negative and high significant relationship with $N_{60}$.

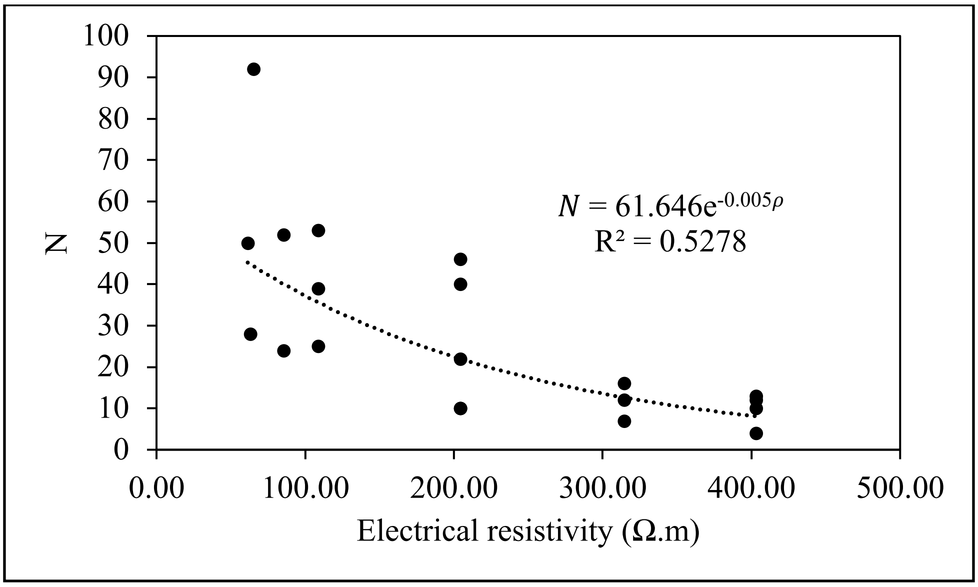


Figure 4.13 Seasonal classification: relationship between electrical resistivity and N-value

Figure 4.13 above depicts a relationship between electrical resistivity and N-value for seasonal classification on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES. Electrical resistivity's functional relationship with N-value was a exponential function. It was discovered that the trend of electrical resistivity reversed from N-value. The $R^2$ value for the relationship between electrical resistivity and N-value was 0.5278. Thus, for seasonal classification, there had the moderate negative relationship between electrical resistivity and N-value.

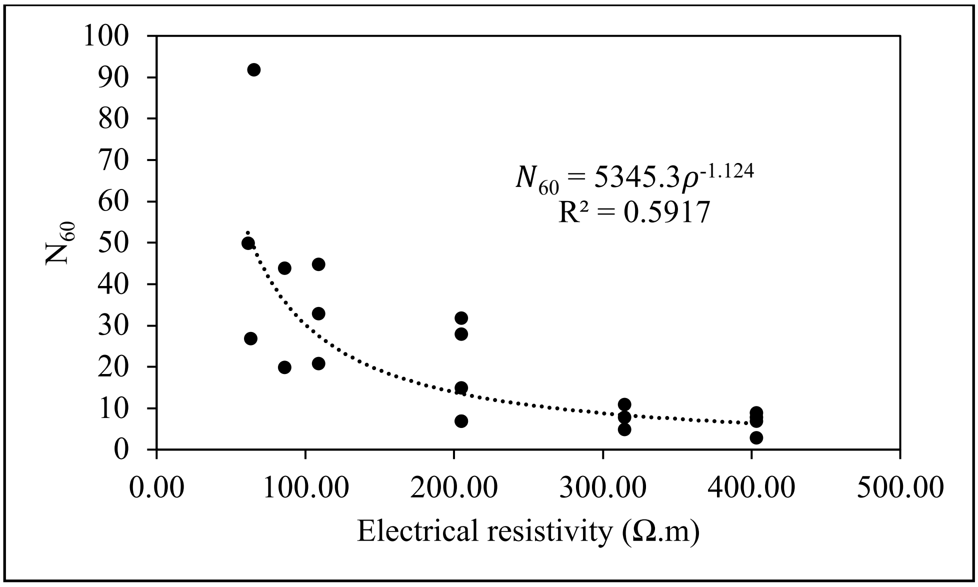


Figure 4.14 Seasonal classification: relationship between electrical resistivity and $N_{60}$ on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES

Figure 4.14 above depicts a relationship between electrical resistivity and $N_{60}$ for seasonal classification. The power function was the functional relationship of electrical resistivity with $N_{60}$. It was found the trend of $N_{60}$ decreased with an increasing of electrical resistivity. The relationship between electrical resistivity and $N_{60}$ was $R^2$ at 0.5917. Thus, there was the moderate negative relationship between electrical resistivity and $N_{60}$ for seasonal classification.

4.3.2 Electrical Resistivity and Shear Wave Velocity

Table 4.12 Seasonal classification: the relationship of electrical resistivity with shear wave velocity for sand layers in Phuket

| **Dataset (Seasonal classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-3 | SPT-3 | $V_s$ | -0.8038** | -5.7331 | 0.00002 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

As presented in Table 4.12, the $r$ value between electrical resistivity and shear wave velocity for seasonal classification on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES was -0.8038. It reveals that decreasing of shear wave velocity was accompanied by an increasing of electrical resistivity. Since the t-distribution for testing hypothesis was found to equal -5.7331, which significant with the p-value equal 0.00002. There was a very statistical high significant relationship between electrical resistivity and shear wave velocity since the p-value becomes less than 0.01. The null hypothesis was not supported. Thus, electrical resistivity seemed to have a very strong negative and high significant relationship with shear wave velocity.

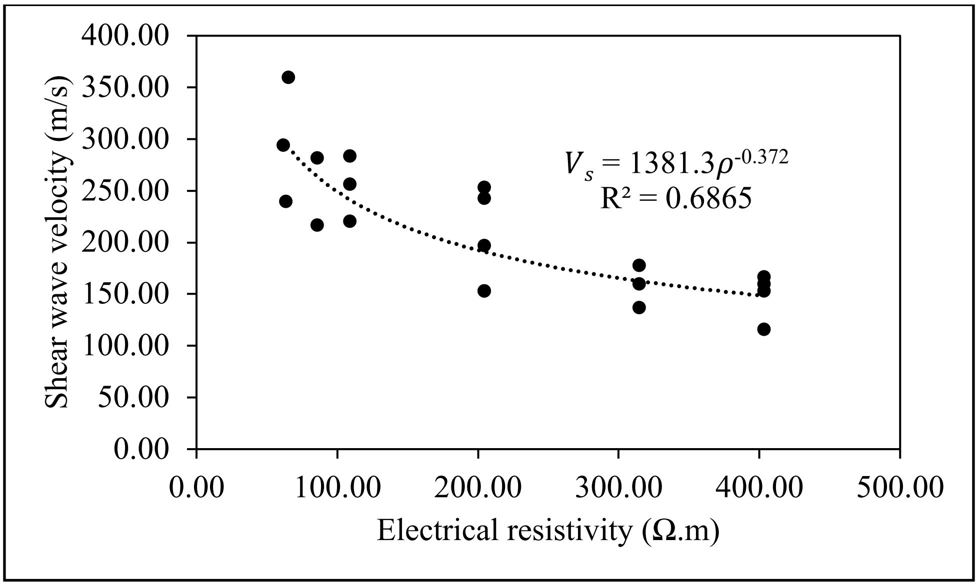


Figure 4.15 Seasonal classification: relationship between electrical resistivity and shear wave velocity on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES

Figure 4.15 depicts a relationship between electrical resistivity and shear wave velocity for seasonal classification. The power function was used to describe the functional relationship between electrical resistivity and shear wave velocity. It was noticed the trend of shear wave velocity decreased while electrical resistivity increased. The $R^2$ value for the relationship between electrical resistivity and shear wave velocity was 0.6865. As a result, for seasonal classification, the strong negative relationship between electrical resistivity and shear wave velocity was found.

4.3.3 Electrical Resistivity and Friction Angle

Table 4.13 Seasonal classification: the relationship of electrical resistivity with friction angle for sand layers in Phuket

| **Dataset (Seasonal classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-3 | SPT-3 | $\emptyset$ | -0.7035** | -4.1996 | 0.0005 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

As given in Table 4.13, the $r$ value between electrical resistivity and friction angle for seasonal classification on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES was -0.7035. It clearly shows that a decreasing of friction angle was happened while electrical resistivity increased. As the t-distribution for testing hull hypothesis was found to equal -4.1996, which significant with the p-value equal 0.0005. There was the high significant relationship between electrical resistivity and friction angle when the p-value is less than 0.01. The null hypothesis was rejected. Therefore, there would be found that electrical resistivity had the strong negative and highly significant relationship with friction angle.

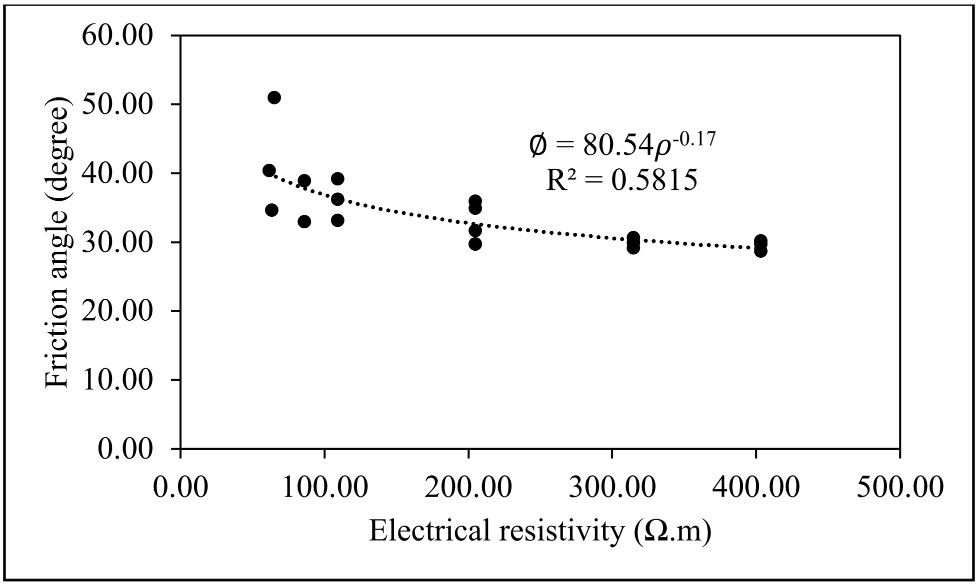


Figure 4.16 Seasonal classification: relationship between electrical resistivity and friction angle on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES

Figure 4.16 shows a relationship between electrical resistivity and friction angle for seasonal classification. The power function described the functional relationship between electrical resistivity and friction angle. Friction angle decreased with an increase electrical resistivity. The $R^2$ of the relationship between electrical resistivity and friction angle was 0.5815. As a result, there was found the moderate negative relationship between electrical resistivity and friction angle for seasonal classification.

4.3.4 Electrical Resistivity and Young's Modulus

Table 4.14 Seasonal classification: the relationship of electrical resistivity with Young's modulus for sand layers in Phuket

| **Dataset (Seasonal classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-3 | SPT-3 | $E_s$ | -0.7035** | -4.1996 | 0.0005 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

The $r$ value between electrical resistivity and Young's modulus for seasonal classification on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES was -0.7035, as shown in Table 4.14. It explains that Young's modulus decreased with an increasing of electrical resistivity. Since the t-distribution for testing hull hypothesis was found to equal -4.1996, which significant with the p-value was equal 0.0005. Electrical resistivity and Young's modulus had a high significant relationship as the p-value was less than 0.01. Thus, the null hypothesis was not supported. Accordingly, electrical resistivity was found to have the strongly negative and highly significant relationship with Young's modulus.

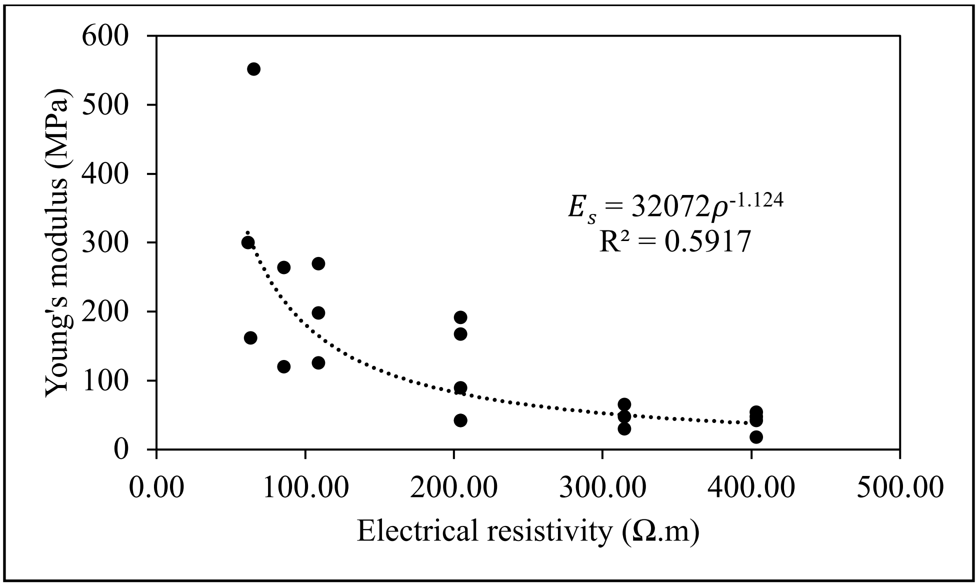


Figure 4.17 Seasonal classification: relationship between electrical resistivity and Young's modulus on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES

Figure 4.17 depicts a relationship between electrical resistivity and Young's modulus for seasonal classification. The power function was the functional relationship between electrical resistivity and Young's modulus. A decreasing of young's modulus was accompanied by an increasing electrical resistivity. The $R^2$ value for the relationship between electrical resistivity and Young's modulus was 0.5917.

Therefore, for seasonal classification, there was the moderate negative relationship between electrical resistivity and Young's modulus.

4.3.5 Electrical Resistivity and Relative Density

Table 4.15 Seasonal classification: the relationship of electrical resistivity with relative density for sand layers in Phuket

| **Dataset (Seasonal classification)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-3 | SPT-3 | $D_r$ | -0.7851** | -5.3783 | 0.00004 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

The $r$ value between electrical resistivity and relative density for seasonal classification on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES was -0.7851, as viewed in Table 4.15. It presents that relative density declined with an increasing of electrical resistivity. Since the t-distribution for testing hypothesis was found to equal -5.3783, which significant with the p-value was equal 0.00004. Electrical resistivity and relative density had a very high significant relationship. The null hypothesis was not supported due the p-value was less than 0.01. Similarly, the relationship between electrical resistivity and relative density was strongly negative and highly significant.

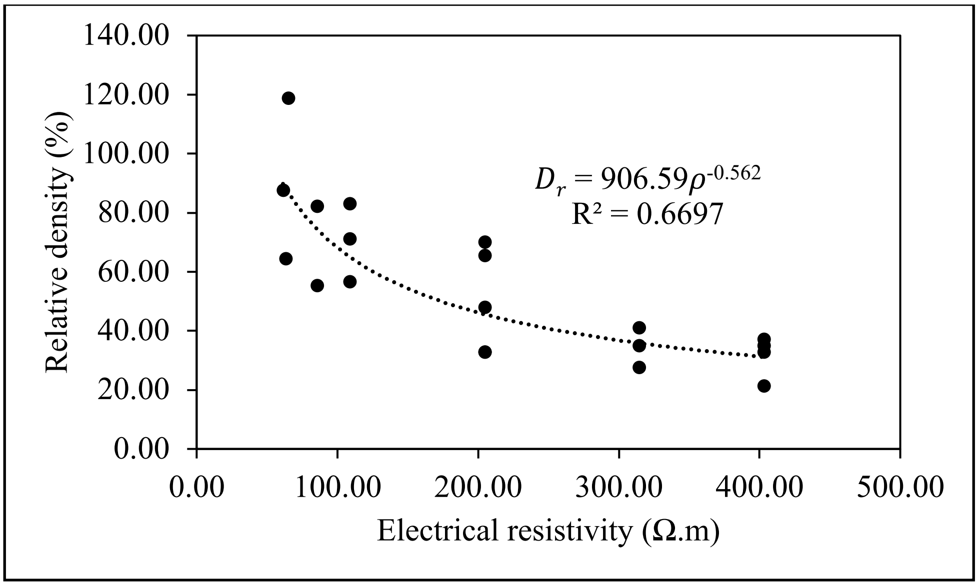


Figure 4.18 Seasonal classification: relationship between electrical resistivity and relative density on sedimentary and metamorphic rocks and the same seasons of employment for SPT and VES

Figure 4.18 depicts a relationship between electrical resistivity and relative density for seasonal classification. The power function was the functional relationship of electrical resistivity with relative density. It was discovered that relative density decreased with an increasing electrical resistivity. The $R^2$ value for the relationship between electrical resistivity and relative density was 0.6697. Therefore, there was the strong negative relationship between electrical resistivity and relative density for seasonal classification.

## 4.4 Correlation Analysis Validation: Rerun of VES Survey on VES-1 and VES-2 in Rainy Season

### 4.4.1 Electrical Resistivity vs. N-value and $N_{60}$

Table 4.16 Validation: the relationship of electrical resistivity with N-value and $N_{60}$ for sand layers in Phuket

| Dataset (Validation) | | Parameters | Pearson coefficient (r) | t-distribution | Significance (p-value) |
|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ |
| VES-1 (Validation) | SPT-1 | $N$ | -0.4886** | -4.4797 | 0.00003 |
| VES-2 (Validation) | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |
| VES-1 (Validation) | SPT-1 | $N_{60}$ | -0.5149** | -4.8049 | 0.00001 |
| VES-2 (Validation) | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

**. Correlation is highly significant at the 0.01 level (2-tailed).

Table 4.16 views the Pearson coefficient $(r)$ of electrical resistivity with geotechnical parameters for validation of sand layers in Phuket. Geotechnical parameters included N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density. The relationship of electrical resistivity and geotechnical parameters were moderate, linear, and negative. Meanwhile, there was the highly significant relationship of electrical resistivity with N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density (p-value < 0.01).

The $r$ value between electrical resistivity and N-value was -0.4886 for validation, as shown in Table 4.16. It demonstrates that N-value decreased when electrical resistivity increased. Since the t-distribution for testing hypothesis was found to equal -4.4797, which significant with the p-value was equal 0.00003. There was a very high statistically significant relationship between electrical resistivity and N-value as the p-value was less than 0.01. So, the alternative hypothesis was not rejected. Likewise, electrical resistivity had the moderately negative and highly significant relationship with N-value.

The $r$ value between electrical resistivity and $N_{60}$ was -0.5149 for validation, as shown by Table 4.16. It reveals that a decreasing of $N_{60}$ was occurred with an increasing of electrical resistivity. Since the t-distribution for testing hypothesis was found to equal -4.8049, which significant with the p-value was equal 0.00001. Statistically, there was a very high significant relationship between electrical resistivity and $N_{60}$. The alternative hypothesis was supported due the p-value was less than 0.01. Equally, electrical resistivity had the moderately negative and highly significant relationship with $N_{60}$.

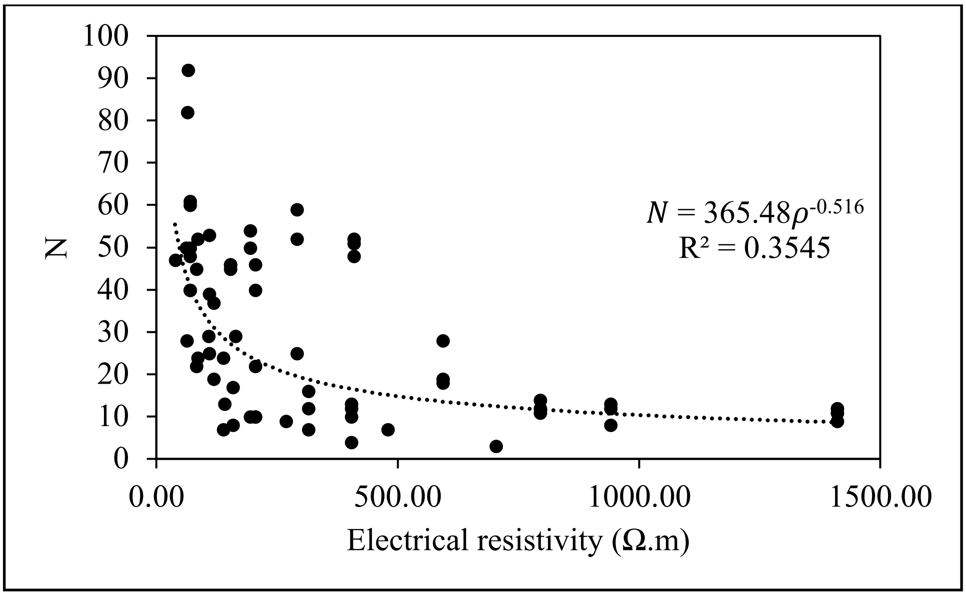


Figure 4.19 Validation: relationship between electrical resistivity and N-value

Figure 4.19 shows a relationship between electrical resistivity and N-value for validation. The power function was the functional relationship of electrical resistivity with N-value. It was discovered that the trend of N-value decreased while electrical resistivity increased. The $R^2$ value for the relationship between electrical resistivity and N-value was 0.3545. Consequently, for validation dataset, there had the moderate negative relationship between electrical resistivity and N-value. This provided the equation $N = 365.48\rho^{-0.516}$ for Phuket's sand layers on sedimentary and metamorphic rocks.

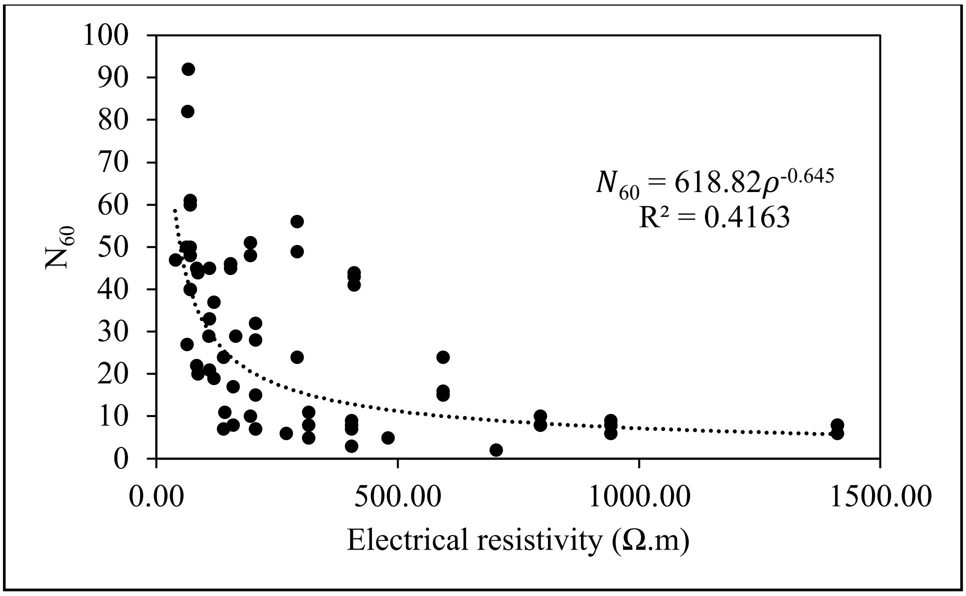


Figure 4.20 Validation: relationship between electrical resistivity and $N_{60}$

Figure 4.20 reflects a relationship between electrical resistivity and $N_{60}$ for validation. The power function was the functional relationship of electrical resistivity with $N_{60}$. It was discovered that the trend of electrical resistivity increased while the trend of $N_{60}$ decreased. The $R^2$ value for the relationship between electrical resistivity and $N_{60}$ was 0.4163. Consequently, there was the moderate negative relationship between electrical resistivity and $N_{60}$ for validation dataset. This suggested the equation for Phuket's sand layers on sedimentary and metamorphic rocks $N_{60} = 618.82\rho^{-0.645}$.

4.4.2 Electrical Resistivity vs. Shear Wave Velocity

Table 4.17 Validation: the relationship of electrical resistivity with shear wave velocity for sand layers in Phuket

| **Dataset (Validation)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ | $\boldsymbol{\rho}$ |
| VES-1 (Validation) | SPT-1 | $V_s$ | -0.5597** | -5.4039 | 0.000001 |
| VES-2 (Validation) | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

**. Correlation is highly significant at the 0.01 level (2-tailed).

The $r$ value between electrical resistivity and shear wave velocity for validation was -0.5597, as presented in Table 4.17. It shows that shear wave velocity decreased with an increase of electrical resistivity. Since the t-distribution for testing hypothesis was found to equal -5.4039, which significant with the p-value was equal 0.000001. There had a very high statistically significant relationship between electrical resistivity and shear wave velocity. The alternative hypothesis was supported while the p-value was less than 0.01. Similarly, electrical resistivity had the moderately negative and highly significant relationship with shear wave velocity.

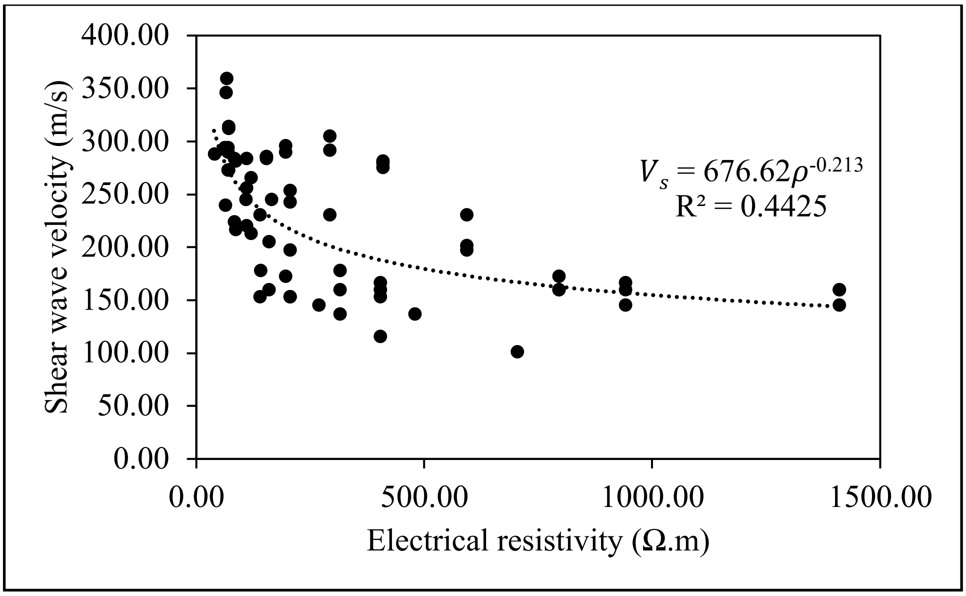


Figure 4.21 Validation: relationship between electrical resistivity and shear wave velocity

Figure 4.21 presents a relationship between electrical resistivity and shear wave velocity for validation. The power function was used to describe the functional relationship between electrical resistivity and shear wave velocity. It was discovered that the trend of shear wave velocity decreased while electrical resistivity increased. The $R^2$ value for the relationship between electrical resistivity and shear wave velocity was 0.4425. Thus, for validation dataset, the moderate negative relationship between electrical resistivity and shear wave velocity was found. This offered the equation for sedimentary and metamorphic rocks in the sand layers in Phuket $V_s = 676.62\rho^{-0.213}$.

4.4.3 Electrical Resistivity vs. Friction Angle

Table 4.18 Validation: the relationship of electrical resistivity with friction angle for sand layers in Phuket

| **Dataset (Validation)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | ***ρ*** | ***ρ*** | ***ρ*** |
| VES-1 (Validation) | SPT-1 | ∅ | -0.5149** | -4.8049 | 0.00001 |
| VES-2 (Validation) | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

**. Correlation is highly significant at the 0.01 level (2-tailed).

The $r$ value between electrical resistivity and friction angle for validation was -0.5149, as mentioned in Table 4.18. It reveals that as an increasing of electrical resistivity was happened, friction angle decreased. Due the t-distribution for testing hypothesis was found to equal -4.8049, which significant with the p-value was equal 0.00001. There was a very high statistically significant relationship between electrical resistivity and friction angle. The p-value was less than 0.01, and the alternative hypothesis was not rejected. Thus, electrical resistivity had the moderately negative and highly significant relationship with friction angle.

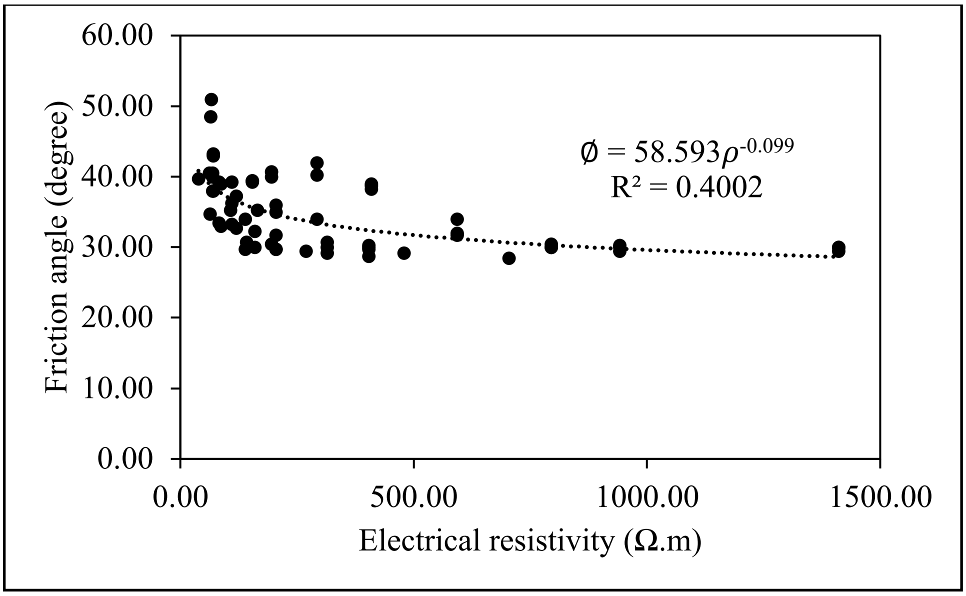


Figure 4.22 Validation: relationship between electrical resistivity with friction angle

Figure 4.22 reflects a relationship between electrical resistivity and friction angle for validation. The power function described the functional relationship between electrical resistivity and friction angle. The trend of friction angle declined when electrical resistivity increased. The relationship between electrical resistivity and friction angle was $R^2$ at 0.4002. Thus, there was found the moderate negative relationship between electrical resistivity and friction angle for validation dataset. This suggested the equation $\emptyset = 58.593\rho^{-0.099}$ for sedimentary and metamorphic rocks in the sand layers in Phuket.

4.4.4 Electrical Resistivity vs. Young's Modulus

Table 4.19 Validation: the relationship of electrical resistivity with Young's modulus for sand layers in Phuket

| Dataset (Validation) | | Parameters | Pearson coefficient (r) | t-distribution | Significance (p-value) |
|---|---|---|---|---|---|
| | | | **$\rho$** | **$\rho$** | **$\rho$** |
| VES-1 (Validation) | SPT-1 | $E_s$ | -0.5149** | -4.8049 | 0.00001 |
| VES-2 (Validation) | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

**. Correlation is highly significant at the 0.01 level (2-tailed).

As mentioned in Table 4.19, the $r$ value between electrical resistivity and Young's modulus for validation was -0.5149. It demonstrates a decline of Young's modulus while electrical resistivity increased. As the t-distribution for testing hypothesis was found to equal -4.8049, which significant with the p-value was equal 0.00001. A high statistically significant relationship between electrical resistivity and Young's modulus was found because the p-value was less than 0.01. The alternative hypothesis was supported. Accordingly, electrical resistivity was found to have the moderately negative and highly significant relationship with Young's modulus.

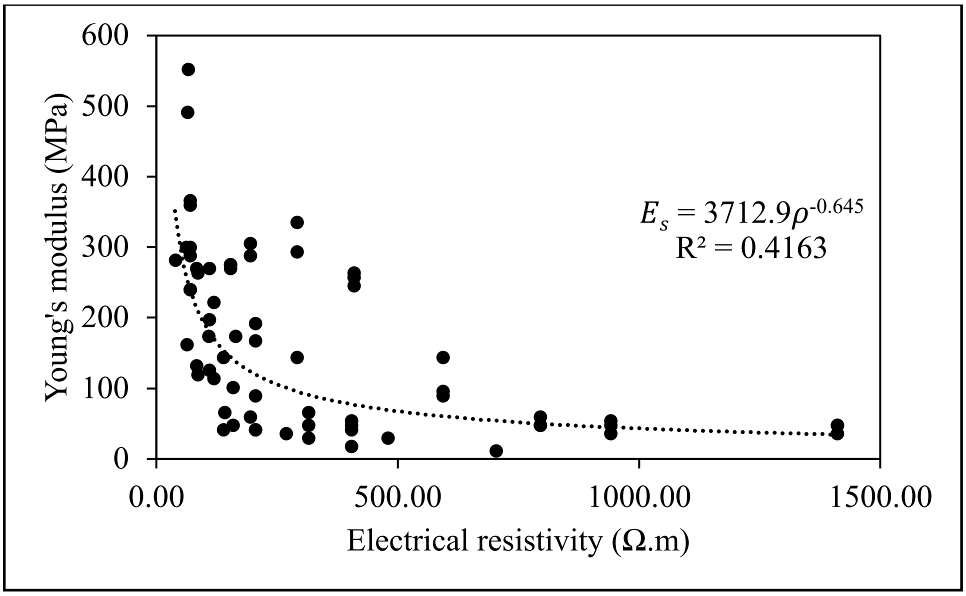


Figure 4.23 Validation: relationship between electrical resistivity and Young's modulus

Figure 4.23 shows a relationship between electrical resistivity and Young's modulus for validation. The power function was the functional relationship between electrical resistivity and Young's modulus. It was discovered that a decreasing of young's modulus was occurred when electrical resistivity increased. The $R^2$ value for the relationship between electrical resistivity and Young's modulus was 0.4163. Hence, for validation dataset, there was the moderate negative relationship between electrical resistivity and Young's modulus. This gave the equation $E_s = 3712.9\rho^{-0.645}$ for sedimentary and metamorphic rocks in the sand layers in Phuket.

4.4.5 Electrical Resistivity vs. Relative Density

Table 4.20 Validation: the relationship of electrical resistivity with relative density for sand layers in Phuket

| **Dataset (Validation)** | | **Parameters** | **Pearson coefficient (r)** | **t-distribution** | **Significance (p-value)** |
|---|---|---|---|---|---|
| | | | ***ρ*** | ***ρ*** | ***ρ*** |
| VES-1 (Validation) | SPT-1 | $D_r$ | -0.5521** | -5.2978 | 0.000002 |
| VES-2 (Validation) | SPT-2 | | | | |
| VES-3 | SPT-3 | | | | |

**. Correlation is highly significant at the 0.01 level (2-tailed).

As presented in Table 4.20, the $r$ value between electrical resistivity and relative density for validation was -0.5521. It demonstrates relative density decreased with an increasing electrical resistivity. Since the t-distribution for testing hypothesis was found to equal -5.2978, which significant with the p-value was equal 0.000002. Electrical resistivity and relative density had a very high statistically significant relationship. The p-value was less than 0.01; thus, the alternative hypothesis was supported. Similarly, the relationship between electrical resistivity and relative density was moderately negative and highly significant.

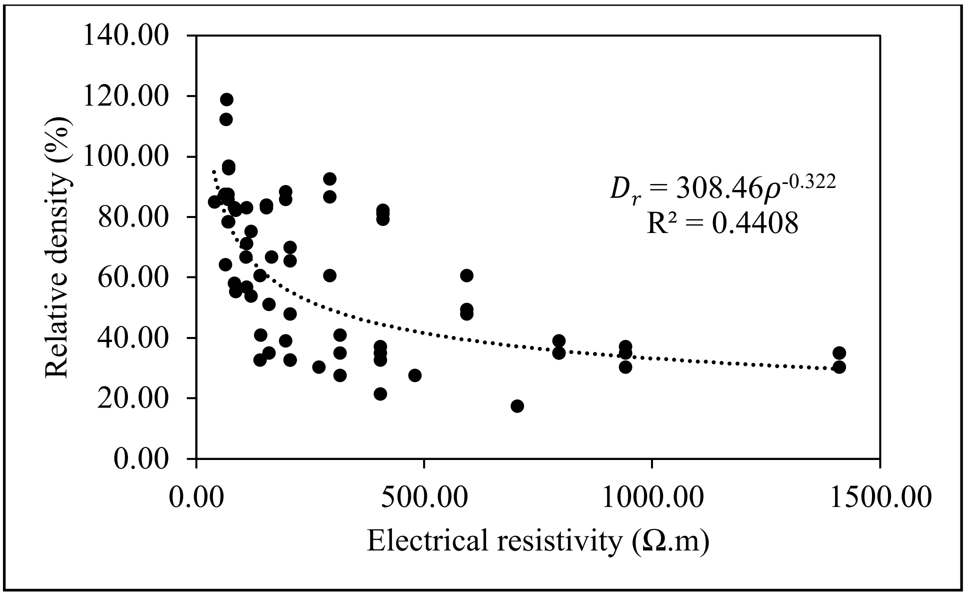


Figure 4.24 Validation: relationship between electrical resistivity and relative density

Figure 4.24 depicts a relationship between electrical resistivity and relative density for validation. The power function was the functional relationship between electrical resistivity and relative density. It was discovered that the trend of while relative density reduced as electrical resistivity increased. $R^2$ = 0.4408 for the relationship between electrical resistivity and relative density. Hence, there was the moderate negative relationship between electrical resistivity and relative density for validation dataset. This suggested the equation $D_r = 308.46\rho^{-0.322}$ for sedimentary and metamorphic rocks in the sand layers in Phuket.

**4.5 Summary of Testing Model Function for the Relationship between Electrical Resistivity and Geotechnical Parameters**

Table 4.21 Testing model function for the relationship between electrical resistivity and geotechnical parameters for sand layers in Phuket

| **Dataset** | **Parameters** | **Coefficient of determination ($R^2$)** | | |
|---|---|---|---|---|
| | | **Linear regression** | **Exponential function** | **Power function** |
| | | $\rho$ | $\rho$ | $\rho$ |
| All data | $N$ | 0.0000007 | 0.000002 | 0.0002 |
| | $N_{60}$ | 0.0002 | 0.0004 | 0.00004 |
| | $V_s$ | 0.0046 | 0.0043 | 0.0053 |
| | $\emptyset$ | 0.0002 | 0.0002 | 0.0001 |
| | $E_s$ | 0.0002 | 0.0004 | 0.00004 |
| | $D_r$ | 0.0020 | 0.0018 | 0.0031 |
| Geological classification | $N$ | 0.0595 | 0.0584 | 0.0372 |
| | $N_{60}$ | 0.0607 | 0.0583 | 0.0357 |
| | $V_s$ | 0.0479 | 0.0470 | 0.0288 |
| | $\emptyset$ | 0.0607 | 0.0603 | 0.0402 |
| | $E_s$ | 0.0607 | 0.0583 | 0.0357 |
| | $D_r$ | 0.0524 | 0.0510 | 0.0312 |
| Seasonal classification | $N$ | 0.4917 | 0.5278 | 0.5143 |
| | $N_{60}$ | 0.4949 | 0.5719 | 0.5917 |
| | $V_s$ | 0.6461 | 0.6714 | 0.6865 |
| | $\emptyset$ | 0.4949 | 0.5101 | 0.5815 |
| | $E_s$ | 0.4949 | 0.5719 | 0.5917 |
| | $D_r$ | 0.6164 | 0.6554 | 0.6697 |
| Validation | $N$ | 0.2387 | 0.2871 | 0.3545 |
| | $N_{60}$ | 0.2651 | 0.3359 | 0.4163 |
| | $V_s$ | 0.3133 | 0.3441 | 0.4425 |
| | $\emptyset$ | 0.2651 | 0.2783 | 0.4002 |
| | $E_s$ | 0.2651 | 0.3359 | 0.4163 |
| | $D_r$ | 0.3048 | 0.3485 | 0.4408 |

Table 4.21 above indicates the relationship between electrical resistivity and geotechnical parameters for sand layers in Phuket using linear regression, exponential function, and power function. N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density are included in geotechnical parameters. These were divided into four datasets: all data, geotechnical classification, seasonal classification, and validation. The findings of model function were reported, following which function suggested the highest result of coefficient of determination, $R^2$, in validation dataset.

Table 4.22 Model function of validation dataset for the relationship between electrical resistivity and geotechnical parameters for sand layers in Phuket

| **Parameters** | **Function** | **Equation** | **Coefficient of determination ($R^2$)** |
|---|---|---|---|
| | $\rho$ | $\rho$ | $\rho$ |
| $\boldsymbol{N}$ | Power | $N = 365.48\rho^{-0.516}$ | 0.3545 |
| $\boldsymbol{N_{60}}$ | Power | $N_{60} = 618.82\rho^{-0.645}$ | 0.4163 |
| $\boldsymbol{V_s}$ | Power | $V_s = 676.62\rho^{-0.213}$ | 0.4425 |
| $\emptyset$ | Power | $\emptyset = 58.593\rho^{-0.099}$ | 0.4002 |
| $\boldsymbol{E_s}$ | Power | $E_s = 3712.9\rho^{-0.645}$ | 0.4163 |
| $\boldsymbol{D_r}$ | Power | $D_r = 308.46\rho^{-0.322}$ | 0.4408 |

After testing the model function and validating the data, the relationship between electrical resistivity and geotechnical parameters in sedimentary and metamorphic rocks in the same employment seasons as SPT and VES, is shown in Table 4.22 above. It reflects function, equation and $R^2$. Thus, the results show that the relationship of electrical resistivity with geotechnical parameters for sand layers in Phuket.

The electrical resistivity data obtained from VES was related to selected geotechnical parameters, by Pearson correlation coefficient and least squares method. They include SPT N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density. Electrical resistivity should be useful for predicting the geotechnical parameters.

It is critical to understand that $r$ does not equal $R^2$. $r$ denotes the strength of a linear relationship between two variables. $R^2$ measures how well the independent variable predicts the dependent variable within the context of the model function.

The Pearson correlation coefficient provided satisfactory results on sand layers in Phuket. That was reasonable to study the quantitative relationship between electrical resistivity and geotechnical parameter estimations. There was found to be a moderate negative relationship between electrical resistivity and geotechnical parameters. It is highly statistical significance on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods for sand layers in Phuket. This was happened after data validation was done.

The findings revealed that there was no relationship between electrical resistivity and N-value for dataset of all data. For geological classification, a statistically significant weak negative relationship of electrical resistivity with N-value was discovered. Notably, for seasonal classification, a strong negative relationship between electrical resistivity and N-value was discovered, which was highly significant. A moderately negative relationship of electrical resistivity with N-value with high statistical significance was determined for validation. Thus, there was found to be a moderate negative relationship between electrical resistivity and N-value. It is high statistical significance on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods for sand layers in Phuket.

The results showed that there was no relationship of electrical resistivity with $N_{60}$ for dataset of all data. For geological classification, a weak negative relationship between electrical resistivity and $N_{60}$ with statistically significance was found. Curiously, for seasonal classification, a strong negative relationship of electrical resistivity with $N_{60}$ was determined with a high statistically significance. For validation, there was shown a moderate negative relationship between electrical resistivity and $N_{60}$ that was highly significance. Consequently, there was discovered to be a moderate negative relationship between electrical resistivity and $N_{60}$. It is high statistical significance on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods for sand layers in Phuket.

The results would show that there was no relationship between electrical resistivity and shear wave velocity for dataset of all data. It was discovered that there was a weak negative relationship between electrical resistivity and shear wave velocity for geological classification. It was statistically insignificant. Surprisingly, for seasonal classification, a strong negative relationship of electrical resistivity with shear wave velocity was discovered with a high statistical significance. For validation, a moderately negative relationship between electrical resistivity and shear wave velocity was found to be highly significant. Therefore, there was found to be a moderate negative relationship between electrical resistivity and shear wave velocity. It is high statistical significance on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods for sand layers in Phuket.

The results would explain, stating that for dataset of all data there was no relationship between electrical resistivity and friction angle. It was realized that a weak negative relationship between electrical resistivity and friction angle was statistically significant for geological classification. Remarkably, for seasonal classification, a strong negative relationship between electrical resistivity and friction angle was discovered with a high statistical significance. For validation, a moderately negative relationship between electrical resistivity and friction angle was found to be highly significant. As a result, there was disclosed to be a moderate negative relationship between electrical resistivity and friction angle. It is a high statistically significance on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods for sand layers in Phuket.

The findings would describe, stating that there was no relationship between electrical resistivity and Young's modulus for dataset of all data. A weak negative relationship between electrical resistivity and Young's modulus was noticed to be statistically significant for geological classification. Interestingly, a strong negative relationship between electrical resistivity and Young's modulus was found with high statistical significance for seasonal classification. A moderately negative relationship between electrical resistivity and Young's modulus was found to be highly significant for validation. Hence, there was revealed to be a moderate negative relationship between electrical resistivity and Young's modulus. It is high statistical significance on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods for sand layers in Phuket.

The results would indicate that there was no relationship between electrical resistivity and relative density for dataset of all data. It was discovered that there was a statistically insignificant weak negative relationship between electrical resistivity and relative density for geological classification. Notably, a strong negative relationship between electrical resistivity and relative density with high statistical significance was discovered for seasonal classification. A moderately negative relationship of electrical resistivity with relative density was discovered to be highly significant for validation purposes. Subsequently, there was determined to be a moderate negative relationship between electrical resistivity and relative density. It is highly statistically significance on sedimentary in the same employment seasons of ERM and conventional methods for sand layers in Phuket.

There were four datasets that discussed geological and seasonal factors that may influence the relationship between resistivity and certain geotechnical parameters. Dataset one, electrical resistivity did not show a significant difference in the level of relationship with geotechnical data. While, all data from sedimentary and metamorphic rocks and igneous rocks in Phuket was combined. Furthermore, there was no relationship between electrical resistivity and geotechnical parameters, all data. Dataset two, the weak negative linear relationship between electrical resistivity and geotechnical parameters was found in the dataset of geological classification. It was sedimentary and metamorphic rocks in different employment seasons of SPT and VES. Moreover, electrical resistivity had a weak negative statistically significant relationship with N-value, $N_{60}$, friction angle, and Young's modulus. But, it was a weak negative statistically insignificant relationship with shear wave velocity and relative density. Dataset three and four, the alternative hypothesis was supported by the results of seasonal classification and validation. Thus, electrical resistivity was discovered to be highly statistically significant correlated with geotechnical data. That measured on sedimentary and metamorphic rocks in Phuket during the same employment seasons of SPT and VES. Moreover, the seasonal classification results revealed a statistically significant strong negative linear relationship for sand layers in Phuket of electrical resistivity with geotechnical parameters. The findings of validation relationship between electrical resistivity and geotechnical parameters for sand layers in Phuket was a high statistically significant, moderate, negative, and linear.

Based on data classification, it was the same employment seasons of SPT and VES on sedimentary and metamorphic rocks for sand layers in Phuket. The findings showed significant difference in the level of the relationship between electrical resistivity and geotechnical parameters. Previous research found that as the number of blows (N-value) increased, the soil resistivity decreased because the compaction process is driven out the void in the soil (Razali & Osman, 2011). The decrease in soil resistivity occurred as the degree of compaction increased (Kowalczyk et al., 2014).

This would be found the same geological environment of sedimentary and metamorphic rocks and the same employment seasons of SPT and VES. The $r$ value between electrical resistivity and geotechnical data was fit with highly significant. In a recent study, the same formation of rock/soil and water saturation were suggested to use the linear relationship between electrical resistivity and N-value (Devi et al., 2017). Moreover, there was no significant relationship found in the level of electrical resistivity and geotechnical parameters for the dataset of all data. Then, the weak negative relationship between electrical resistivity and geotechnical parameters was determined for the dataset of geological classification. It revealed a significant difference in level of electrical resistivity with N-value, $N_{60}$, friction angle, and Young's modulus. However, it was not a significant different in level of electrical resistivity with shear wave velocity and relative density.

Geotechnical parameters, such as N-value, $N_{60}$, and geotechnical parameter estimations, have been integrated with ERM results. As shown in Table 4.22, the correlation between electrical resistivity and geotechnical parameters was highly significant. Electrical resistivity had the moderately negative relationship with selected geotechnical parameters. Based on the correlation analyses, electrical resistivity can be used to predict geotechnical parameters. Power function model with $R^2$ greater than 0.35 are for electrical resistivity with N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density. According to the findings, that electrical resistivity can be a predictor of some selected geotechnical parameters for sand layers in Phuket.

# CHAPTER 5
# CONCLUSIONS

A comprehensive study of electrical resistivity and geotechnical parameter estimations for Phuket sand layers was presented. It is based on electrical resistivity using ERM, SPT data, N-value correction, and geotechnical parameter estimations. The Pearson correlation coefficient was used to examine the relationship between electrical resistivity and geotechnical parameter estimations. The following conclusions can be drawn from the findings:

By developing quantitative correlations of sand layers in Phuket, VES data can be used to predict geotechnical parameters for site investigation. The electrical resistivity range corresponding to the sedimentary and metamorphic rocks on sand layers in Phuket is from 38.74 Ω.m to 1409.91 Ω.m, according to the data. The employment of SPT and VES was then done during the same seasons.

There is a direct relationship between electrical resistivity and geotechnical parameters for sand layers in Phuket. It focused on sedimentary and metamorphic rocks in the same employment seasons of ERM and conventional methods. Electrical resistivity has a moderately negative relationship with N-value, $N_{60}$, shear wave velocity, friction angle, Young's modulus, and relative density, $\boldsymbol{r}$, which are at -0.4886, -0.5149, -0.5597, -0.5149, -0.5149, and -0.5521, respectively, and the relationship is highly significant. It indicates that electrical resistivity is inversely proportional to geotechnical parameter estimations using a power function. However, there is a weak negative relationship of electrical resistivity with N-value, $N_{60}$, friction angle, and Young's modulus on sedimentary and metamorphic rocks in different employment seasons of ERM and conventional methods, but the relationship is significant.

According to these findings, geology and seasoning may be factors in the correlations between ERM and conventional methods for estimating geotechnical parameters. Electrical resistivity is a considerable indirect predictor of these selected geotechnical parameters. Thus, power function is proposed as a function to estimate geotechnical parameters from electrical resistivity. The findings of this study, ERM can be applied as an alternative tool for estimating geotechnical parameters. It is good for geotechnical investigations of subsurface sand layers in Phuket.

Additional research studies have been proposed to improve understanding of the relationships. Electrical resistivity and geotechnical parameters should have more correlation studies in various geological environments. It is also considered about the seasonal use of ERM and conventional methods. It is recommended that geotechnical data for each parameter be conducted in the field. Also, at the same time and place, data on geotechnical parameters and electrical resistivity should be collected.

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# APPENDIX

**Appendix1** Summary of 58 electrical resistivity data using VES for sand layers in Phuket

| Station | Study area | VES station | Depth (m) | Electrical resistivity (Ω.m) |
|---|---|---|---|---|
| **Station-1** | Mai Khao | VES-1 | 1.50 | 926.26 |
| | | | 2.00 | 906.96 |
| | | | 2.50 | 726.93 |
| | | | 3.50 | 802.15 |
| | | | 5.00 | 763.90 |
| | | | 6.50 | 757.72 |
| | | | 8.00 | 745.06 |
| | | | 9.50 | 682.27 |
| | | | 11.00 | 601.41 |
| | | | 12.50 | 513.24 |
| | | | 14.00 | 461.00 |
| | | | 18.50 | 363.32 |
| | | | 20.00 | 337.15 |
| | | | 21.50 | 312.74 |
| | | | 23.00 | 290.97 |
| | | | 24.50 | 280.48 |
| | | | 26.00 | 236.64 |

| | | | | |
|---|---|---|---|---|
| | | VES-1 (validation) | 1.50 | 1409.91 |
| | | | 2.00 | 940.93 |
| | | | 2.50 | 794.71 |
| | | | 3.50 | 592.75 |
| | | | 5.00 | 408.84 |
| | | | 6.50 | 291.33 |
| | | | 8.00 | 194.29 |
| | | | 9.50 | 158.66 |
| | | | 11.00 | 138.81 |
| | | | 12.50 | 118.90 |
| | | | 14.00 | 107.30 |
| | | | 18.50 | 163.97 |
| | | | 20.00 | 82.36 |
| | | | 21.50 | 153.31 |
| | | | 23.00 | 68.83 |
| | | | 24.50 | 69.81 |
| | | | 26.00 | 63.73 |
| **Station-2** | Choeng Thale | VES-2 | 1.50 | 172.74 |
| | | | 2.00 | 72.04 |
| | | | 2.50 | 90.98 |
| | | | 3.50 | 19.17 |
| | | | 23.00 | 50.14 |
| | | VES-2 (validation) | 1.50 | 703.34 |

| | | | | |
|---|---|---|---|---|
| | | | 2.00 | 479.00 |
| | | | 2.50 | 268.30 |
| | | | 3.50 | 140.62 |
| | | | 23.00 | 38.74 |
| **Station-3** | Ratsada | VES-3 | 1.50 | 402.97 |
| | | | 2.00 | 314.39 |
| | | | 2.50 | 204.50 |
| | | | 3.50 | 108.81 |
| | | | 5.00 | 85.68 |
| | | | 8.00 | 63.17 |
| | | | 9.50 | 65.13 |
| | | | 11.00 | 61.34 |
| **Station-4** | Kathu | VES-4 | 0.50 | 64.44 |
| | | | 1.50 | 58.25 |
| | | | 2.50 | 313.12 |
| | | | 3.50 | 265.86 |
| | | | 4.50 | 188.05 |
| | | | 5.50 | 178.53 |

**Appendix 2** Summary of 84 data of each geotechnical parameter for sand layers in Phuket

| Station | Study area | SPT station | BH | Depth (m) | N value | $N_{60}$ | Shear wave velocity (m/s) | Friction angle (degree) | Young's modulus (MPa) | Relative density (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Station-1** | Mai Khao | SPT-1 | BH-1 | 1.50 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.00 | 8 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.50 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 3.50 | 28 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | | | | 5.00 | 51 | 43 | 279.91 | 38.75 | 258 | 81.31 |
| | | | | 6.50 | 52 | 49 | 292.27 | 40.25 | 294 | 86.80 |
| | | | | 8.00 | 54 | 51 | 296.17 | 40.75 | 306 | 88.55 |
| | | | | 14.00 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 18.50 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 20.00 | 22 | 22 | 224.22 | 33.50 | 132 | 58.16 |
| | | | | 21.50 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 23.00 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |
| | | | | 24.50 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | | | | 26.00 | 82 | 82 | 346.58 | 48.50 | 492 | 112.29 |
| | | | BH-2 | 1.50 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |
| | | | | 2.50 | 14 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | | | | 3.50 | 18 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | | | | 5.00 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 6.50 | 59 | 56 | 305.48 | 42.00 | 336 | 92.79 |
| | | | 8.00 | 50 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | | | 9.50 | 8 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | 11.00 | 7 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | 12.50 | 19 | 19 | 213.60 | 32.75 | 114 | 54.05 |
| | | | 21.50 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | | | 23.00 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | | | 24.50 | 61 | 61 | 314.25 | 43.25 | 366 | 96.85 |
| | | BH-3 | 1.50 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | 2.00 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | 2.50 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | 3.50 | 19 | 16 | 201.79 | 32.00 | 96 | 49.60 |
| | | | 5.00 | 48 | 41 | 275.53 | 38.25 | 246 | 79.40 |
| | | | 6.50 | 25 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | | | 8.00 | 10 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | | | 9.50 | 17 | 17 | 205.88 | 32.25 | 102 | 51.13 |
| | | | 11.00 | 24 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | | | 12.50 | 37 | 37 | 266.32 | 37.25 | 222 | 75.43 |
| | | | 20.00 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | 21.50 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | | | 23.00 | 48 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | | | 24.50 | 60 | 60 | 312.54 | 43.00 | 360 | 96.05 |
| Choeng Thale | SPT-2 | BH-1 | 1.50 | 3 | 2 | 101.39 | 28.50 | 12 | 17.54 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Station-2** | | | | 2.00 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 3.50 | 13 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 23.00 | 47 | 47 | 288.27 | 39.75 | 282 | 85.01 |
| **Station-3** | Ratsada | SPT-3 | BH-1 | 1.50 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 2.50 | 22 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | | | | 3.50 | 53 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 5.00 | 24 | 20 | 217.26 | 33.00 | 120 | 55.45 |
| | | | BH-2 | 2.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 25 | 21 | 220.80 | 33.25 | 126 | 56.82 |
| | | | | 8.00 | 28 | 27 | 239.95 | 34.75 | 162 | 64.43 |
| | | | BH-3 | 1.50 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 39 | 33 | 256.43 | 36.25 | 198 | 71.23 |
| | | | | 5.00 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | | | BH-4 | 1.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 2.00 | 16 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 2.50 | 46 | 32 | 253.83 | 36.00 | 192 | 70.14 |
| | | | BH-5 | 1.50 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |
| | | | | 2.00 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.50 | 40 | 28 | 242.85 | 35.00 | 168 | 65.61 |
| | | | | 9.50 | 92 | 92 | 360.04 | 51.00 | 552 | 118.94 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 11.00 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |
| **Station-4** | Kathu | SPT-4 | BH-1 | 0.50 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 1.50 | 6 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 2.50 | 3 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 3.50 | 2 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 4.50 | 5 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 5.50 | 2 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | BH-2 | 0.50 | 8 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 1.50 | 5 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 2.50 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 3.50 | 3 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 4.50 | 3 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 5.50 | 5 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | BH-3 | 0.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 1.50 | 5 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 2.50 | 2 | 1 | 80.60 | 28.25 | 6 | 12.40 |
| | | | | 3.50 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 4.50 | 3 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 5.50 | 4 | 4 | 127.53 | 29.00 | 24 | 24.80 |

**Appendix 3** Dataset one, all data: sedimentary and igneous rock for sand layers in Phuket

| Station | SPT station | BH-# | VES station | Depth (m) | Electrical resistivity (Ω.m) | N value | $N_{60}$ | Shear wave velocity (m/s) | Friction angle (degree) | Young's modulus (MPa) | Relative density (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station-1** | SPT-1 | BH-1 | VES-1 | 1.50 | 926.26 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.00 | 906.96 | 8 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.50 | 726.93 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 3.50 | 802.15 | 28 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | | | | 5.00 | 763.90 | 51 | 43 | 279.91 | 38.75 | 258 | 81.31 |
| | | | | 6.50 | 757.72 | 52 | 49 | 292.27 | 40.25 | 294 | 86.80 |
| | | | | 8.00 | 745.06 | 54 | 51 | 296.17 | 40.75 | 306 | 88.55 |
| | | | | 14.00 | 461.00 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 18.50 | 363.32 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 20.00 | 337.15 | 22 | 22 | 224.22 | 33.50 | 132 | 58.16 |
| | | | | 21.50 | 312.74 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 23.00 | 290.97 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |
| | | | | 24.50 | 280.48 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | | | | 26.00 | 236.64 | 82 | 82 | 346.58 | 48.50 | 492 | 112.29 |
| | | BH-2 | | 1.50 | 926.26 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 906.96 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |
| | | | | 2.50 | 726.93 | 14 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | | | | 3.50 | 802.15 | 18 | 15 | 197.52 | 31.75 | 90 | 48.02 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 5.00 | 763.90 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | 6.50 | 757.72 | 59 | 56 | 305.48 | 42.00 | 336 | 92.79 |
| | 8.00 | 745.06 | 50 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | 9.50 | 682.27 | 8 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 11.00 | 601.41 | 7 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | 12.50 | 513.24 | 19 | 19 | 213.60 | 32.75 | 114 | 54.05 |
| | 21.50 | 312.74 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | 23.00 | 290.97 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | 24.50 | 280.48 | 61 | 61 | 314.25 | 43.25 | 366 | 96.85 |
| BH-3 | 1.50 | 926.26 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.00 | 906.96 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.50 | 726.93 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 3.50 | 802.15 | 19 | 16 | 201.79 | 32.00 | 96 | 49.60 |
| | 5.00 | 763.90 | 48 | 41 | 275.53 | 38.25 | 246 | 79.40 |
| | 6.50 | 757.72 | 25 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | 8.00 | 745.06 | 10 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | 9.50 | 682.27 | 17 | 17 | 205.88 | 32.25 | 102 | 51.13 |
| | 11.00 | 601.41 | 24 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | 12.50 | 513.24 | 37 | 37 | 266.32 | 37.25 | 222 | 75.43 |
| | 20.00 | 337.15 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | 21.50 | 312.74 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | 23.00 | 290.97 | 48 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | 24.50 | 280.48 | 60 | 60 | 312.54 | 43.00 | 360 | 96.05 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station-2** | SPT-2 | BH-1 | VES-2 | 1.50 | 172.74 | 3 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 2.00 | 72.04 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 90.98 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 3.50 | 19.17 | 13 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 23.00 | 50.14 | 47 | 47 | 288.27 | 39.75 | 282 | 85.01 |
| **Station-3** | SPT-3 | BH-1 | VES-3 | 1.50 | 402.97 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 2.50 | 204.50 | 22 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | | | | 3.50 | 108.81 | 53 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 5.00 | 85.68 | 24 | 20 | 217.26 | 33.00 | 120 | 55.45 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 25 | 21 | 220.80 | 33.25 | 126 | 56.82 |
| | | | | 8.00 | 63.17 | 28 | 27 | 239.95 | 34.75 | 162 | 64.43 |
| | | BH-3 | | 1.50 | 402.97 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 314.39 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 39 | 33 | 256.43 | 36.25 | 198 | 71.23 |
| | | | | 5.00 | 85.68 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | | BH-4 | | 1.50 | 402.97 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 2.00 | 314.39 | 16 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 2.50 | 204.50 | 46 | 32 | 253.83 | 36.00 | 192 | 70.14 |
| | | BH-5 | | 1.50 | 402.97 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |
| | | | | 2.00 | 314.39 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.50 | 204.50 | 40 | 28 | 242.85 | 35.00 | 168 | 65.61 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 9.50 | 65.13 | 92 | 92 | 360.04 | 51.00 | 552 | 118.94 |
| | | | | 11.00 | 61.34 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |
| **Station-4** | SPT-4 | BH-1 | VES-4 | 0.50 | 64.44 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 1.50 | 58.25 | 6 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 2.50 | 313.12 | 3 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 3.50 | 265.86 | 2 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 4.50 | 188.05 | 5 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 5.50 | 178.53 | 2 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | BH-2 | | 0.50 | 64.44 | 8 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 1.50 | 58.25 | 5 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 2.50 | 313.12 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 3.50 | 265.86 | 3 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 4.50 | 188.05 | 3 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 5.50 | 178.53 | 5 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | BH-3 | | 0.50 | 64.44 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 1.50 | 58.25 | 5 | 4 | 127.53 | 29.00 | 24 | 24.80 |
| | | | | 2.50 | 313.12 | 2 | 1 | 80.60 | 28.25 | 6 | 12.40 |
| | | | | 3.50 | 265.86 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 4.50 | 188.05 | 3 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 5.50 | 178.53 | 4 | 4 | 127.53 | 29.00 | 24 | 24.80 |

**Appendix 4** Dataset two, geological classification: sedimentary (in different employment seasons of SPT and VES) for sand layers in Phuket

| Station | SPT station | BH-# | VES station | Depth (m) | Electrical resistivity (Ω.m) | N value | $N_{60}$ | Shear wave velocity (m/s) | Friction angle (degree) | Young's modulus (MPa) | Relative density (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station-1** | SPT-1 | BH-1 | VES-1 | 1.50 | 926.26 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.00 | 906.96 | 8 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.50 | 726.93 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 3.50 | 802.15 | 28 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | | | | 5.00 | 763.90 | 51 | 43 | 279.91 | 38.75 | 258 | 81.31 |
| | | | | 6.50 | 757.72 | 52 | 49 | 292.27 | 40.25 | 294 | 86.80 |
| | | | | 8.00 | 745.06 | 54 | 51 | 296.17 | 40.75 | 306 | 88.55 |
| | | | | 14.00 | 461.00 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 18.50 | 363.32 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 20.00 | 337.15 | 22 | 22 | 224.22 | 33.50 | 132 | 58.16 |
| | | | | 21.50 | 312.74 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 23.00 | 290.97 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |
| | | | | 24.50 | 280.48 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | | | | 26.00 | 236.64 | 82 | 82 | 346.58 | 48.50 | 492 | 112.29 |
| | | BH-2 | | 1.50 | 926.26 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 906.96 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2.50 | 726.93 | 14 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | 3.50 | 802.15 | 18 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | 5.00 | 763.90 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | 6.50 | 757.72 | 59 | 56 | 305.48 | 42.00 | 336 | 92.79 |
| | 8.00 | 745.06 | 50 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | 9.50 | 682.27 | 8 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 11.00 | 601.41 | 7 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | 12.50 | 513.24 | 19 | 19 | 213.60 | 32.75 | 114 | 54.05 |
| | 21.50 | 312.74 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | 23.00 | 290.97 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | 24.50 | 280.48 | 61 | 61 | 314.25 | 43.25 | 366 | 96.85 |
| BH-3 | 1.50 | 926.26 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.00 | 906.96 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.50 | 726.93 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 3.50 | 802.15 | 19 | 16 | 201.79 | 32.00 | 96 | 49.60 |
| | 5.00 | 763.90 | 48 | 41 | 275.53 | 38.25 | 246 | 79.40 |
| | 6.50 | 757.72 | 25 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | 8.00 | 745.06 | 10 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | 9.50 | 682.27 | 17 | 17 | 205.88 | 32.25 | 102 | 51.13 |
| | 11.00 | 601.41 | 24 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | 12.50 | 513.24 | 37 | 37 | 266.32 | 37.25 | 222 | 75.43 |
| | 20.00 | 337.15 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | 21.50 | 312.74 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 23.00 | 290.97 | 48 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | | | | 24.50 | 280.48 | 60 | 60 | 312.54 | 43.00 | 360 | 96.05 |
| **Station-2** | SPT-2 | BH-1 | VES-2 | 1.50 | 172.74 | 3 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 2.00 | 72.04 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 90.98 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 3.50 | 19.17 | 13 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 23.00 | 50.14 | 47 | 47 | 288.27 | 39.75 | 282 | 85.01 |
| **Station-3** | SPT-3 | BH-1 | VES-3 | 1.50 | 402.97 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 2.50 | 204.50 | 22 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | | | | 3.50 | 108.81 | 53 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 5.00 | 85.68 | 24 | 20 | 217.26 | 33.00 | 120 | 55.45 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 25 | 21 | 220.80 | 33.25 | 126 | 56.82 |
| | | | | 8.00 | 63.17 | 28 | 27 | 239.95 | 34.75 | 162 | 64.43 |
| | | BH-3 | | 1.50 | 402.97 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 314.39 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 39 | 33 | 256.43 | 36.25 | 198 | 71.23 |
| | | | | 5.00 | 85.68 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | | BH-4 | | 1.50 | 402.97 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 2.00 | 314.39 | 16 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 2.50 | 204.50 | 46 | 32 | 253.83 | 36.00 | 192 | 70.14 |
| | | BH-5 | | 1.50 | 402.97 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2.00 | 314.39 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.50 | 204.50 | 40 | 28 | 242.85 | 35.00 | 168 | 65.61 |
| | 9.50 | 65.13 | 92 | 92 | 360.04 | 51.00 | 552 | 118.94 |
| | 11.00 | 61.34 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |

**Appendix 5** Dataset three, seasonal classification: sedimentary in the same employment seasons of SPT and VES for sand layers in Phuket

| Station | SPT station | BH-# | VES station | Depth (m) | Electrical resistivity (Ω.m) | N value | $N_{60}$ | Shear wave velocity (m/s) | Friction angle (degree) | Young's modulus (MPa) | Relative density (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station-3** | SPT-3 | BH-1 | VES-3 | 1.50 | 402.97 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 2.50 | 204.50 | 22 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | | | | 3.50 | 108.81 | 53 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 5.00 | 85.68 | 24 | 20 | 217.26 | 33.00 | 120 | 55.45 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 25 | 21 | 220.80 | 33.25 | 126 | 56.82 |
| | | | | 8.00 | 63.17 | 28 | 27 | 239.95 | 34.75 | 162 | 64.43 |
| | | BH-3 | | 1.50 | 402.97 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 314.39 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 39 | 33 | 256.43 | 36.25 | 198 | 71.23 |
| | | | | 5.00 | 85.68 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | | BH-4 | | 1.50 | 402.97 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 2.00 | 314.39 | 16 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 2.50 | 204.50 | 46 | 32 | 253.83 | 36.00 | 192 | 70.14 |
| | | BH-5 | | 1.50 | 402.97 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2.00 | 314.39 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.50 | 204.50 | 40 | 28 | 242.85 | 35.00 | 168 | 65.61 |
| | 9.50 | 65.13 | 92 | 92 | 360.04 | 51.00 | 552 | 118.94 |
| | 11.00 | 61.34 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |

**Appendix 6** Dataset four, validation: sedimentary in different employment seasons of SPT and VES for sand layers in Phuket

| **Station** | **SPT station** | **BH-#** | **VES station** | **Depth (m)** | **Electrical resistivity (Ω.m)** | **N value** | **$N_{60}$** | **Shear wave velocity (m/s)** | **Friction angle (degree)** | **Young's modulus (MPa)** | **Relative density (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station-1** | SPT-1 | BH-1 | VES-1 (validation) | 1.50 | 1409.91 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.00 | 940.93 | 8 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 2.50 | 794.71 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 3.50 | 592.75 | 28 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | | | | 5.00 | 408.84 | 51 | 43 | 279.91 | 38.75 | 258 | 81.31 |
| | | | | 6.50 | 291.33 | 52 | 49 | 292.27 | 40.25 | 294 | 86.80 |
| | | | | 8.00 | 194.29 | 54 | 51 | 296.17 | 40.75 | 306 | 88.55 |
| | | | | 14.00 | 107.30 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 18.50 | 163.97 | 29 | 29 | 245.69 | 35.25 | 174 | 66.78 |
| | | | | 20.00 | 82.36 | 22 | 22 | 224.22 | 33.50 | 132 | 58.16 |
| | | | | 21.50 | 153.31 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 23.00 | 68.83 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |
| | | | | 24.50 | 69.81 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | | | | 26.00 | 63.73 | 82 | 82 | 346.58 | 48.50 | 492 | 112.29 |
| | | BH-2 | | 1.50 | 1409.91 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 940.93 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |
| | | | | 2.50 | 794.71 | 14 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | | | | 3.50 | 592.75 | 18 | 15 | 197.52 | 31.75 | 90 | 48.02 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 5.00 | 408.84 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | 6.50 | 291.33 | 59 | 56 | 305.48 | 42.00 | 336 | 92.79 |
| | 8.00 | 194.29 | 50 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | 9.50 | 158.66 | 8 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 11.00 | 138.81 | 7 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | 12.50 | 118.90 | 19 | 19 | 213.60 | 32.75 | 114 | 54.05 |
| | 21.50 | 153.31 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | 23.00 | 68.83 | 40 | 40 | 273.29 | 38.00 | 240 | 78.42 |
| | 24.50 | 69.81 | 61 | 61 | 314.25 | 43.25 | 366 | 96.85 |
| BH-3 | 1.50 | 1409.91 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.00 | 940.93 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 2.50 | 794.71 | 11 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | 3.50 | 592.75 | 19 | 16 | 201.79 | 32.00 | 96 | 49.60 |
| | 5.00 | 408.84 | 48 | 41 | 275.53 | 38.25 | 246 | 79.40 |
| | 6.50 | 291.33 | 25 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | 8.00 | 194.29 | 10 | 10 | 172.72 | 30.50 | 60 | 39.21 |
| | 9.50 | 158.66 | 17 | 17 | 205.88 | 32.25 | 102 | 51.13 |
| | 11.00 | 138.81 | 24 | 24 | 230.77 | 34.00 | 144 | 60.75 |
| | 12.50 | 118.90 | 37 | 37 | 266.32 | 37.25 | 222 | 75.43 |
| | 20.00 | 82.36 | 45 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | 21.50 | 153.31 | 46 | 46 | 286.23 | 39.50 | 276 | 84.10 |
| | 23.00 | 68.83 | 48 | 48 | 290.29 | 40.00 | 288 | 85.91 |
| | 24.50 | 69.81 | 60 | 60 | 312.54 | 43.00 | 360 | 96.05 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station-2** | SPT-2 | BH-1 | VES-2 (validation) | 1.50 | 703.34 | 3 | 2 | 101.39 | 28.50 | 12 | 17.54 |
| | | | | 2.00 | 479.00 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 268.30 | 9 | 6 | 145.85 | 29.50 | 36 | 30.37 |
| | | | | 3.50 | 140.62 | 13 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 23.00 | 38.74 | 47 | 47 | 288.27 | 39.75 | 282 | 85.01 |
| **Station-3** | SPT-3 | BH-1 | VES-3 | 1.50 | 402.97 | 4 | 3 | 115.95 | 28.75 | 18 | 21.48 |
| | | | | 2.50 | 204.50 | 22 | 15 | 197.52 | 31.75 | 90 | 48.02 |
| | | | | 3.50 | 108.81 | 53 | 45 | 284.15 | 39.25 | 270 | 83.18 |
| | | | | 5.00 | 85.68 | 24 | 20 | 217.26 | 33.00 | 120 | 55.45 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 25 | 21 | 220.80 | 33.25 | 126 | 56.82 |
| | | | | 8.00 | 63.17 | 28 | 27 | 239.95 | 34.75 | 162 | 64.43 |
| | | BH-3 | | 1.50 | 402.97 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.00 | 314.39 | 7 | 5 | 137.31 | 29.25 | 30 | 27.73 |
| | | | | 2.50 | 204.50 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 3.50 | 108.81 | 39 | 33 | 256.43 | 36.25 | 198 | 71.23 |
| | | | | 5.00 | 85.68 | 52 | 44 | 282.04 | 39.00 | 264 | 82.25 |
| | | BH-4 | | 1.50 | 402.97 | 10 | 7 | 153.48 | 29.75 | 42 | 32.81 |
| | | | | 2.00 | 314.39 | 16 | 11 | 178.25 | 30.75 | 66 | 41.13 |
| | | | | 2.50 | 204.50 | 46 | 32 | 253.83 | 36.00 | 192 | 70.14 |
| | | BH-5 | | 1.50 | 402.97 | 13 | 9 | 166.80 | 30.25 | 54 | 37.20 |
| | | | | 2.00 | 314.39 | 12 | 8 | 160.42 | 30.00 | 48 | 35.07 |
| | | | | 2.50 | 204.50 | 40 | 28 | 242.85 | 35.00 | 168 | 65.61 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 9.50 | 65.13 | 92 | 92 | 360.04 | 51.00 | 552 | 118.94 |
| | 11.00 | 61.34 | 50 | 50 | 294.23 | 40.50 | 300 | 87.68 |

**Appendix 7.1** The relationship between electrical resistivity and N-value for sand layers in Phuket

| $\rho$ & $N$ | Function | Equation | Coefficient of determination ($R^2$) | Pearson coefficient (r) | t-distribution | Sig. |
|---|---|---|---|---|---|---|
| All data | Linear | $N = 0.0002\rho + 24.302$ | 7E-06 | 0.0027 | 0.0247 | 0.9804 |
| Geological classification | Linear | $N = -0.0173\rho + 37.567$ | 0.0595 | -0.2440* | -2.0129 | 0.0483 |
| Seasonal classification | Exponential | $N = 61.646e^{-0.005\rho}$ | 0.5143 | -0.7012** | -4.1728 | 0.0006 |
| Validation | Power | $N = 365.48\rho^{-0.516}$ | 0.3545 | -0.4886** | -4.4797 | 3E-05 |

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is highly significant at the 0.01 level (2-tailed).

**Appendix 7.2** The relationship between electrical resistivity and corrected N-value ($N_{60}$) for sand layers in Phuket

| $\rho$ & $N_{60}$ | Function | Equation | Coefficient of determination ($R^2$) | Pearson coefficient (r) | t-distribution | Sig. |
|---|---|---|---|---|---|---|
| All data | Linear | $N_{60} = -0.001\rho + 22.467$ | 0.0002 | -0.0134 | -0.1213 | 0.9038 |
| Geological classification | Linear | $N_{60} = -0.0177\rho + 35.026$ | 0.0607 | -0.2464* | -2.0339 | 0.0461 |
| Seasonal classification | Power | $N_{60} = 5345.3\rho^{-1.124}$ | 0.5278 | -0.7035** | -4.1996 | 0.0005 |
| Validation | Power | $N_{60} = 618.82\rho^{-0.645}$ | 0.3545 | -0.5149** | -4.8049 | 1E-05 |

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is highly significant at the 0.01 level (2-tailed).

**Appendix 7.3** The relationship between electrical resistivity and shear wave velocity for sand layers in Phuket

| $\rho$ & $V_s$ | Function | Equation | Coefficient of determination ($R^2$) | Pearson coefficient (r) | t-distribution | Sig. |
|---|---|---|---|---|---|---|
| All data | Linear | $V_s = 0.0171\rho + 194.96$ | 0.0046 | 0.0676 | 0.6136 | 0.5412 |
| Geological classification | Linear | $V_s = -0.0484\rho + 245.31$ | 0.0479 | -0.2189 | -1.7951 | 0.0774 |
| Seasonal classification | Power | $V_s = 1381.3\rho^{-0.372}$ | 0.6865 | -0.8038** | -5.7331 | 2E-05 |
| Validation | Power | $V_s = 676.62\rho^{-0.213}$ | 0.4425 | -0.5597** | -5.4039 | 1E-06 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

**Appendix 7.4** The relationship between electrical resistivity and friction angle for sand layers in Phuket

| $\rho$ & $\emptyset$ | Function | Equation | Coefficient of determination ($R^2$) | Pearson coefficient (r) | t-distribution | Sig. |
|---|---|---|---|---|---|---|
| All data | Linear | $\emptyset = -0.0002\rho + 33.617$ | 0.0002 | -0.0134 | -0.1213 | 0.9038 |
| Geological classification | Linear | $\emptyset = -0.0044\rho + 36.757$ | 0.0607 | -0.2464* | -2.0339 | 0.0461 |
| Seasonal classification | Power | $\emptyset = 80.54\rho^{-0.17}$ | 0.5815 | -0.7035** | -4.1996 | 0.0005 |
| Validation | Power | $\emptyset = 58.593\rho^{-0.099}$ | 0.4002 | -0.5149** | -4.8049 | 1E-05 |

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is highly significant at the 0.01 level (2-tailed).

**Appendix 7.5** The relationship between electrical resistivity and young's modulus for sand layers in Phuket

| $\rho$ & $E_s$ | Function | Equation | Coefficient of determination ($R^2$) | Pearson coefficient (r) | t-distribution | Sig. |
|---|---|---|---|---|---|---|
| All data | Linear | $E_s = -0.0059\rho + 134.8$ | 0.0002 | -0.0134 | -0.1213 | 0.9038 |
| Geological classification | Linear | $E_s = -0.106\rho + 210.16$ | 0.0607 | -0.2464* | -2.0339 | 0.0461 |
| Seasonal classification | Power | $E_s = 32072\rho^{-1.124}$ | 0.5917 | -0.7035** | -4.1996 | 0.0005 |
| Validation | Power | $E_s = 3712.9\rho^{-0.645}$ | 0.4163 | -0.5149** | -4.8049 | 1E-05 |

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is highly significant at the 0.01 level (2-tailed).

**Appendix 7.6** The relationship between electrical resistivity and relative density for sand layers in Phuket

| $\rho$ & $D_r$ | Function | Equation | Coefficient of determination ($R^2$) | Pearson coefficient (r) | t-distribution | Sig. |
|---|---|---|---|---|---|---|
| All data | Linear | $D_r = 0.0043\rho + 50.194$ | 0.0020 | 0.0446 | 0.4043 | 0.6870 |
| Geological classification | Linear | $D_r = -0.0198\rho + 68.578$ | 0.0524 | -0.2290 | -1.8819 | 0.0644 |
| Seasonal classification | Power | $D_r = 906.59\rho^{-0.562}$ | 0.6697 | -0.7851** | -5.3783 | 4E-05 |
| Validation | Power | $D_r = 308.46\rho^{-0.322}$ | 0.4408 | -0.5521** | -5.2978 | 2E-06 |

**. Correlation is highly significant at the 0.01 level (2-tailed).

**Appendix 8** Summary of the relationship between electrical resistivity and geotechnical parameters for sand layers in Phuket

| **Dataset (Validation)** | | **Parameters** | **Function** | **Equation** | **Coefficient of determination ($R^2$)** | **Pearson coefficient (r)** | **t-distribution** | **Sig.** |
|---|---|---|---|---|---|---|---|---|
| | | | $\rho$ | $\rho$ | $\rho$ | $\rho$ | $\rho$ | $\rho$ |
| VES-1 (Validation) | SPT-1 | $N$ | Power | $N = 365.48\rho^{-0.516}$ | 0.3545 | -0.4886** | -4.4797 | 3E-05 |
| | | $N_{60}$ | Power | $N_{60} = 618.82\rho^{-0.645}$ | 0.4163 | -0.5149** | -4.8049 | 1E-05 |
| VES-2 (Validation) | SPT-2 | $V_s$ | Power | $V_s = 676.62\rho^{-0.213}$ | 0.4425 | -0.5597** | -5.4039 | 1E-06 |
| | | $\emptyset$ | Power | $\emptyset = 58.593\rho^{-0.099}$ | 0.4002 | -0.5149** | -4.8049 | 1E-05 |
| VES-3 | SPT-3 | $E_s$ | Power | $E_s = 3712.9\rho^{-0.645}$ | 0.4163 | -0.5149** | -4.8049 | 1E-05 |
| | | $D_r$ | Power | $D_r = 308.46\rho^{-0.322}$ | 0.4408 | -0.5521** | -5.2978 | 2E-06 |

**. Correlation is significant at the 0.01 level (2-tailed).

# VITAE

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