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Development of A Soil Resistivity Calculator

Muhd Anas Ezhar and Siow Chun Lim*
Faculty of Engineering, Multimedia University, Jalan Multimedia, 63100 Cyberjaya, Selangor, Malaysia.
**Corresponding author: clsiow@mmu.edu.my*

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***Abstract* – Soil resistivity is an important parameter for designing electrical earthing system. The measurement of soil resistivity is greatly influenced by moisture content, temperature, porosity, degree of saturation, number of soil layer(s), and frequency of lightning current. Researchers have proposed various methodologies to provide an approximation of soil resistivity using the listed parameters. In order to ease the process of estimating soil resistivity at a particular area, there is a pressing need to devise a simple tool that enables the calculation of soil resistivity in the most accurate manner. As such, this research proposes a reliable tool for quick evaluation of soil resistivity based on various methodologies using Microsoft Excel's built-in-functions and Visual Basic Application (VBA) Next, the developed tool was validated using two methods, in which the output value of the calculator was compared with data retrieved from IEEE Std 142-2007 and data reported in past studies. The validation results revealed that the developed calculator may serve as a significant application in future due to its time-saving and cost-effective attributes.**

Keywords* — *Soil resistivity, earthing, grounding, electrical safety.

I. INTRODUCTION

To date, both quality and performance of grounding system ascertain reliable protection of electrical operation, so as to offer a safe environment for many [1]. Without a proper grounding system, people may be exposed to a detrimental environment. Environmental factors such as localisation effect and compression level of soil were shown to affect soil resistivity [2-4]. Hence, the element of soil resistivity should be taken into account while designing the grounding system, due to its major impact on ground resistance.

Various methods are widely applied to measure soil resistivity. The common methods used in determining soil resistivity at both site and laboratory appear to be tedious, time consuming, and costly. Nevertheless, the readings may differ at varying periods of time due to changes in parameters, such as temperature, soil type, and moisture content. These parameters may affect the resistivity of soil in a particular area. Incorrect soil resistivity leads to inaccurate designing of the grounding system [5]. In this paper, the parameters of moisture content, temperature, porosity, degree of saturation, number of soil layer(s), and frequency of lightning current were selected to evaluate the values of soil resistivity. The numerous techniques deployed to calculate soil resistivity using these parameters should be consolidated for ease and cost-efficiency purposes. Hence, a simple soil resistivity tool is proposed in this study to ease future engineers inspect soil resistivity from time to time.

II. SOIL RESISTIVITY PARAMETERS

A comparison on the regression/formula models for the relationship of the selected parameters with soil resistivity reported in the past studies was made. Correlation coefficient (R^2) of the regression model was used to select a good model if more than one regression was present for each soil type. The equations are described in terms of moisture content w

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(%), temperature T (°C), porosity Φ (%), degree of saturation S_R (%), and frequency f (Hz). A constant unit was applied for soil resistivity values - (Ω m).

A. Moisture Content

As reported in [6], moisture content can be used to determine soil resistivity using Eq. (1) with correlation coefficient of 0.7718. This equation is only applicable to clayey silt soil type and it is expressed as follows:

$$\rho = e^{\frac{ln\frac{w}{152.87}}{-0.312}} \text{ , } R^2 = 0.7718 \qquad (1)$$

For sandy soil, soil resistivity is expressed in Eq. (2) - (4) as a function of moisture content [7-9]. Reference [10] alternatively asserted that resistivity of sandy soil may be calculated more precisely using relative density (%) and water content as permeating fluids (%), which refers to distilled water Eq. (5) or tap water Eq. (6) [10]. The regression coefficients are:

$$\rho = 4881.5\, w^{-0.757} \text{ , } R^2 = 0.675 \qquad (2)$$

$$\rho = e^{\frac{w-25.16}{-3.78}} \text{ , } R^2 = 0.964 \qquad (3)$$

$$\rho = \mathrm{e}^{\frac{\mathrm{w}-46.859}{-4.467}} \text{ , } R^2 = 0.5375 \qquad (4)$$

$$\rho = 527(4.9-\frac{D_r}{100})w^{-0.832} \text{ , } R^2 = 0.915 \qquad (5)$$

$$\rho = 732(4.6-\frac{D_r}{100})w^{-1.258} \text{ , } R^2 = 0.881 \qquad (6)$$

Upon comparing the correlation coefficient in Eq. (2)-(6) to calculate the resistivity of sandy soil type, Eq. (3) yielded the highest correlation coefficient. If distilled water and tap water parameters are used, Eq. (5) and Eq. (6) can be applied as the regression model due to the high correlation coefficient scores.

A geophysical survey was conducted to determine the soil properties in relation to moisture content [11]. The equations developed at sites 1, 2, and 3 were considered because R^2 > 0.8. Based on the data reported in [11], Eq. (7) at site 1 ranged at 1-10 %, while Eq. (8) at site 2 ranged at 20-34 %, and Eq. (9) at site 3 ranged at 10-20 %. After taking the 10 soil samples with different profiles, it can be assumed that the formula is general. In order to cater to specific soil type, a comparison was made with the data presented in [12]. As a result, the formula is in accordance with clay soil type.

$$\rho = -7856\mathrm{w} + 171.81, R^2 = 0.9409 \qquad (7)$$

$$\rho = -1.7044\mathrm{w} + 126.28, R^2 = 0.8903 \qquad (8)$$

$$\rho = -5.778\mathrm{w} + 163.32, R^2 = 0.954 \qquad (9)$$

As for silt soil sample, the formula was obtained from the data analysis that involved median filtering [9]. The developed model is expressed in Eq. (10). Besides, regression model in Eq. (11) was introduced to calculate soil resistivity in peat soil type, which was limited to the range of 285-315 % [13]. For expansive soils, volumetric water content was used as the variable to calculate soil electrical resistivity, given as function in Eq. (12) [14].

$$\rho = 271.08e^{-11.81w}, R^2 = 0.965 \qquad (10)$$

$$\rho = -46.78 \ln(\mathrm{w}) + 271.41, R^2 = 0.8916 \qquad (11)$$

$$\rho = 1828.4e^{-0.1214w}, R^2 = 0.96 \qquad (12)$$

Kibria *et al.* [15] proposed Eq. (13) – (16) from four sample sites to calculate electrical resistivity in compacted clays. Among the formulas, the highest correlation coefficient was derived from Eq. (15).

$$\rho = 328.03w^{-1.351} \text{ , } R^2 = 0.88 \qquad (13)$$

$$\rho = 306.65w^{-1.331} \text{ , } R^2 = 0.81 \qquad (14)$$

$$\rho = 247.03w^{-1.224} \text{ , } R^2 = 0.96 \qquad (15)$$

$$\rho = 119.26w^{-1.094}, R^2 = 0.87 \qquad (16)$$

B. Temperature

The resistivity measurement in relation to temperature was investigated in China [16]. Most soil types covered were sand and clay soils. The proposed models (Eq. 17 & Eq. 18) yielded high value of R^2. The regression coefficients are as follows:

$$\rho = 91.54e^{\frac{-T}{23.17}} + 24.3 \text{ , } R^2 = 0.99 \qquad (17)$$

$$\rho = 60.09e^{\frac{-T}{16.88}} + 9.55, R^2 = 0.997 \qquad (18)$$

C. Porosity

Besides moisture content, porosity (%) was also used to determine soil resistivity values in a geophysical survey in Southern Suburb of Kumasi *et al.* [11]. The 10 soil samples were taken from different profiles and were assumed applicable to all soil types. Based on the data reported in [11], Eq. (19) – (24) display the regression models and the highest correlation coefficient was recorded at 0.9925. Hence, Eq. (19) was selected among the rest.

$$\rho = -2.1162\, \Phi + 194.21 \text{ , } R^2 = 0.9925 \qquad (19)$$

$$\rho = -0.7924\, \Phi + 132.03 \text{ , } R^2 = 0.9399 \qquad (20)$$

$$\rho = -2.1995\, \Phi + 181.82 \text{ , } R^2 = 0.8586 \qquad (21)$$

$$\rho = -1.4038\, \Phi + 136.56 \text{ , } R^2 = 0.8567 \qquad (22)$$

$$\rho = -1.2176\, \Phi + 149 \text{ , } R^2 = 0.8442 \qquad (23)$$

$$\rho = -3.6866\, \Phi + 313.14 \text{ , } R^2 = 0.8334 \qquad (24)$$

Another study had provided the empirical formula to determine the correlation between porosity and soil resistivity [17]. The formula can be applied to general soils; $\Phi = 66443\rho^{-2.068}$ with correlation of 0.919 and rewritten in Eq. (25).

In a study on electrical resistivity of expansive soil in [14], a model was proposed to estimate electrical resistivity in terms of porosity and saturation. The formula is expressed as Eq. (26).

$$\rho = e^{-0.48 \ln \frac{\Phi}{66443}} \quad , R^2 = 0.919 \tag{25}$$

$$\rho = 16651.0\Phi^{2.7747} \times e^{-0.0549 S_r} , R^2 = 0.95 \tag{26}$$

Comparing the correlation coefficient between models Eq. (19) and Eq. (25) that may be used in general soil, Eq. (19) yielded the highest correlation coefficient value.

D. Saturation

M. Zhou *et al.* proposed some models to calculate the value of soil resistivity using the concept of soil saturation [18]. The models adhered to their soil types; Eq. (27) for sand, Eq. (28) for silt sand, Eq. (29) for silt, Eq. (30) for silt loam, and Eq. (31) for clay loam. Meanwhile, sand, loess, and clay soil types were assessed by Jia *et al.* [19]. Based on the data trend, the formulas are given in Eq. (32) - (34).

$$\rho = 83458 {S_r}^{-1.4} , R^2 = 0.99 \tag{27}$$

$$\rho = 8542 {S_r}^{-0.98} , R^2 = 0.98 \tag{28}$$

$$\rho = 10451 {S_r}^{-1.05} , R^2 = 0.99 \tag{29}$$

$$\rho = 15074 {S_r}^{-1.24} , R^2 = 0.95 \tag{30}$$

$$\rho = 17646 {S_r}^{-1.33} , R^2 = 0.95 \tag{31}$$

$$\rho = 2748.9 S_r^{-0.6709} , R^2 = 0.832 \tag{32}$$

$$\rho = 441.9 S_r^{-0.6394} , R^2 = 0.885 \tag{33}$$

$$\rho = 336.1 S_r^{-0.6137} , R^2 = 0.903 \tag{34}$$

Equation (27) and Eq. (32) that determined sand soil resistivity served as a function of saturation. Hence, Eq. (27) was selected due to its highest regression coefficient yield.

E. Number of Soil Layer(s)

To compute soil resistivity data of two-layer soil structure, the authors proposed three equations in adherence to IEEE procedures [1].

Equation (35) is used to determine the reflection coefficient. For positive and negative values of K, Eq. (36) and Eq. (37) are applicable, respectively.

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{35}$$

$$\rho = \rho_2 [1 + (\frac{\rho_2}{\rho_1} - 1) \times \left(1 - e^{\frac{-1}{-k(d+2h)}}\right)] \tag{36}$$

$$\rho = \frac{\rho_1}{(1 + \left(\frac{\rho_1}{\rho_2} - 1\right) \times \left(1 - e^{\frac{-1}{-k(d+2h)}}\right))} \tag{37}$$

, where

ρ_1= 1st layer of soil resistivity

ρ_2= 2nd layer of soil resistivity

d = depth of the top layer

h = grid depth

Even though the genetic algorithms proposed by Gonos *et al.* displayed the highest accuracy of soil resistivity in multilayer soil, the IEEE 80 standard claimed that two-layer of soil resistivity structure (SRS) is adequate for approximation of many soil structures [20, 21]. Thus, the formula of two-layer SRS was taken into account in this study.

F. Frequency

S. Visacro *et al.* introduced a low-frequency soil resistivity model that can be promptly applied to general soils in practical problems [22]. The model developed is presented in Eq. (38). The previous collected formulas Eq. (1) – (37) were suitable for soil resistivity at low frequency. By reciprocal, the value of σ in Eq. (38) can be determined.

$$\sigma = \sigma_o + (\sigma_o \times 1.26 \times {\sigma_o}^{-0.73}) \tag{38}$$

III. SOIL RESISTIVITY EVALUATION

Based on the above selected equations, corresponding to soil type and soil parameters as inputs, a set of possible values of soil resistivity is generated. Mean value was computed to obtain a single index of soil resistivity. This value is used for further calculation of two-layer soil Eq. (35) - (37) using $\rho_{1,avg}$ and $\rho_{2,avg}$.

IV. TOOL DEVELOPMENT

In this research, the Microsoft Excel VBA was used to develop a simple soil resistivity tool. Two modes are available in this tool, which are quick estimation mode and detailed calculation mode.

A. Features

A.1 Quick Estimation Mode

In this mode, the tools can help a user in deciding the value of the parameters. The user only needs to select the soil type and the location. Location input helps a user to estimate soil resistivity at a certain area by using data from past studies. This yields a possible range of soil resistivity displayed in the message box for the chosen location. Fig. 1 illustrates the flowchart of the tool in quick estimation mode.

In order to help an user determine the value of the input parameters, the average or range value is obtained from prior studies. The first method involves identifying the parameter(s) (moisture content & etc.) used in the past studies. Next, the user should check the suitability of the average or range value reported in the past studies to be applied to Eq. (1) - (30). In the absence of any suitable equation, it is assumed that no data is available for that particular location. If the equation fits, it means that the location of the soil sample had been assessed previously. After that, the selected outcomes may be applied to determine the average or range value of certain parameter(s) at the particular location. The second method applies when the location of the soil sample is unknown. The procedure is similar to the first method, but the average or range value determined is assumed to be general data. Hence, it can be applied to any location.

A.2 Detailed Calculation Mode

Primarily, the user has to select the number of soil layer(s) to be assessed. Next, the soil type of each layer is chosen. For example, a single layer signifies only one soil type, whereas two layers indicate two types of soil. If the selected soil type has the formula, the available parameters can be listed along with its limitation/recommendation. Then, the user can input the parameter data to obtain the soil resistivity value. Lastly, the possible value of soil resistivity based on each parameter can be listed, together with the average value of all datasets (see Fig. 2).

B. User Interface (UI)

The UI was designed to obtain information from the user. This enables the user to control the flow of the program in interaction.

B.1 Menu

The ‘menu’ sheet functions as the menu-driven interface of this calculator. Figure 3 presents the screenshot of the ‘sheet’.

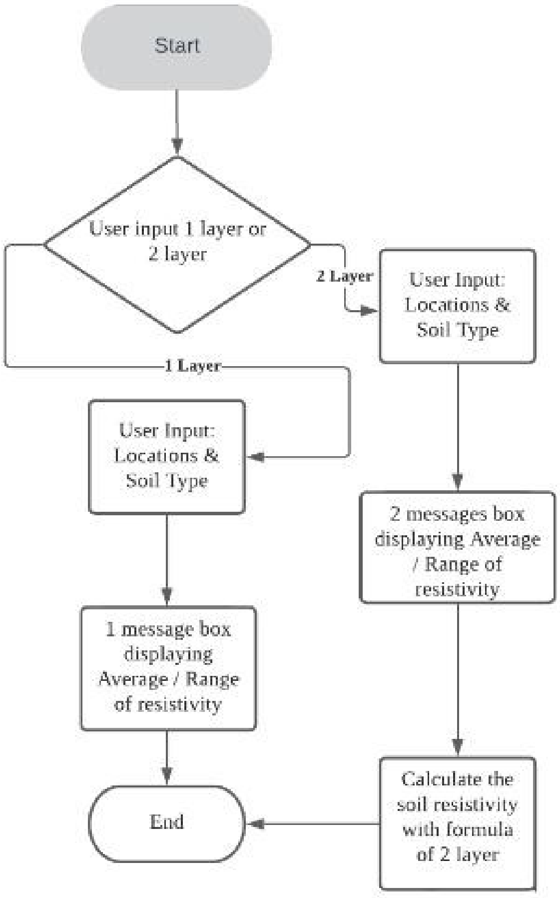


Fig. 1. Flowchart of tool in quick estimation mode.

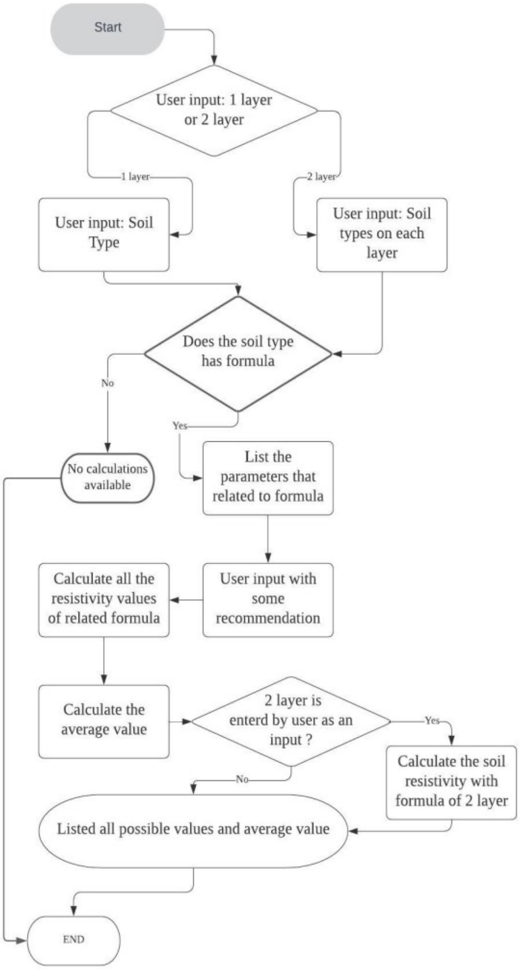


Fig. 2. Methodology for detailed calculation mode.

Fig. 3. Screenshot of ‘Menu’ sheet.

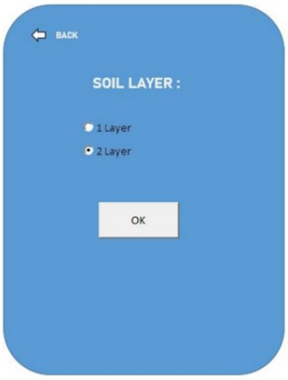
B.2 Menu 2

‘Menu 2’ sheet is the interface that presents user the available mode features on this calculator. Figure 4 displays the screenshot of ‘Menu 2’ sheet.

Fig. 4. Screenshot of 'Menu 2' sheet.

B.3 Soil Layer

The 'Soil Layer' sheet is the interface to present the user the number of soil layer(s) selection. Figure 5 shows the screenshot of 'Soil Layer' sheet.



SOIL LAYER :

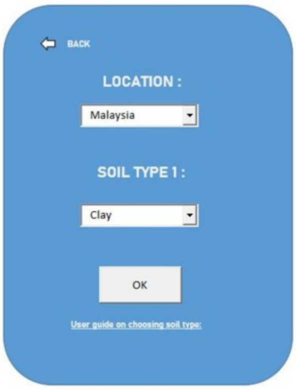
○ 1 Layer

● 2 Layer

Fig. 5. Screenshot of 'Soil Layer' sheet.

B.4 Quick Estimation 1

'Quick Estimation 1' sheet is the interface that enables the user to select the location and the soil type of the 1st layer. Figure 6 presents the screenshot of 'Quick Estimation 1' sheet.



LOCATION : Malaysia

SOIL TYPE 1 : Clay

Fig. 6. Screenshot of 'Quick Estimation 1' sheet.

B.5 Quick Estimation 2

The function of this sheet is similar to 'quick estimation 1', except for the addition of the selection of soil type 2 as the 2nd layer. Figure 7 illustrates the screenshot of 'Quick Estimation 2' sheet.

LOCATION : China

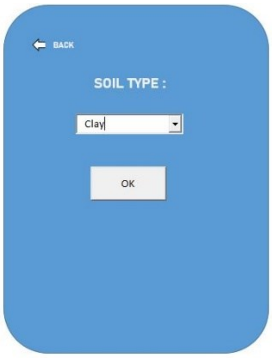
SOIL TYPE 1 : Clay

SOIL TYPE 2 : Clay Loam

Fig. 7. Screenshot of 'Quick Estimation 2' sheet.

B.6 Detailed Calculation 1

'Detailed Calculation 1' sheet is the interface that enables the user to specify the soil type of the 1st layer. Figure 8 presents the screenshot of 'Detailed Calculation 1' sheet.

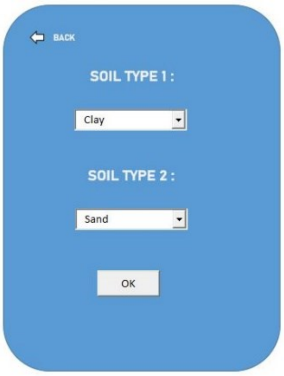


SOIL TYPE : Clay

Fig. 8. Screenshot of 'Detailed Calculation 1' sheet.

B.7 Detailed Calculation 2

The function of this sheet is similar to that of 'Detailed Calculation 1', but with addition of the selection of soil type 2 as the 2nd layer. Figure 9 displays the screenshot of 'Quick Estimation 2' sheet.



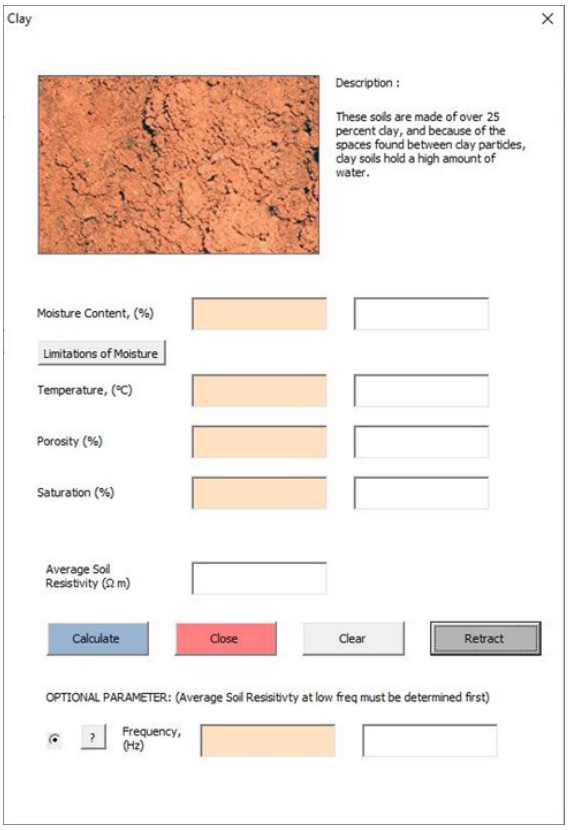
SOIL TYPE 1 : Clay

SOIL TYPE 2 : Sand

Fig. 9. Screenshot of 'Detailed Calculation 1' sheet.

B.8 Userform

'Userform' window is the interface that prompts the user an input to generate a corresponding output. There are userforms for each soil type and a userform 'apparent resistivity' to calculate two-layer soil. Figure 10 presents the screenshot of sample 'Clay' userform, while Fig. 11 is the screenshot of ‘apparent resistivity’ userform.



These soils are made of over 25 percent clay, and because of the spaces found between clay particles, clay soils hold a high amount of water.

Fig. 10. Screenshot of ‘Clay’ Userform.

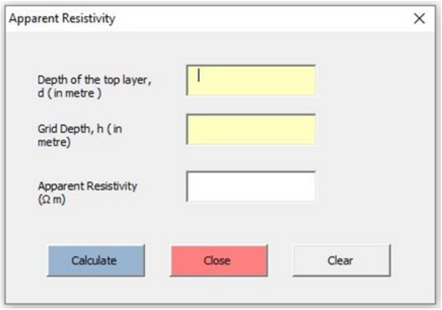


Fig. 11. Screenshot of ‘Apparent Resistivity’ Userform.

V. RESULTS AND DISCUSSION

The developed tool was validated via comparative analysis between the values generated by the calculator and the values obtained from the reviewed dataset. This comparative analysis ascertained how far the results or values generated by the software deviated from the results obtained by the researchers. In the analysis, clay soil type was sampled with different parameters. This selection was made based on the availability of the most relevant datasets to identify the soil type for comparison purpose, which had been implemented based on detailed calculation only. The values of the parameters were retrieved from [11, 16, 19]. Table I tabulates the comparative results with the reviewed dataset.

Table I. The Comparison of Clay Soil Type.

Ref.	Parameter	Input Data	Researchers Output Data (Ωm)	Tool’s Output Data (Ωm)	% Error
[11]	w (%)	18.87	50.07	54.289	8.43
		18.76	50.23	54.722	8.94
		13.05	83.12	87.776	5.6
		11.32	100.39	97.791	2.5
	Φ (%)	49.54	89.04	89.373	0.37
		48.47	90.46	91.638	1.3
		42.17	102.89	104.97	2.02
		46.59	97.93	95.616	2.36
[17]	T (°C)	20	27.54	27.925	1.4
		25.2	23.43	23.054	1.6
		30.5	19.82	19.415	2.04
		34.9	17.13	17.151	0.12
		40.3	15.42	15.07	2.27
		45	13.4	13.729	2.45
[20]	S_r (%)	10	75	81.803	9.07
		50	25	31.466	25.86

Table I shows that the values of the reviewed dataset and the software outputs had differed slightly. While this was expected, the variance was relatively small. This was mainly due to the regression equations and coefficient models developed by the researchers. The present project incorporated the best fit line based on a scatter plot of data points.

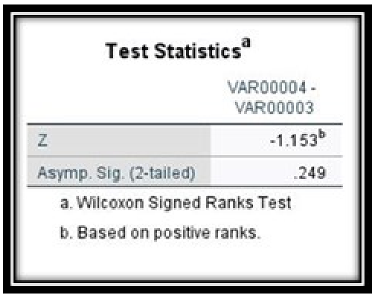
Further validation was made by comparing the estimation value of software results with the standard value of soil resistivity depicted in IEE Std 142-2007. This validation study ensured that the results fell in the acceptable range. The comparison method used was Wilcoxon Signed Rank test using IBM SPSS Statistics software. The comparison of standard values of soil resistivity with the outcomes obtained from the proposed tool for clay soil is presented in Table II [23].

Table II. Comparison of Results with the Standard Values of Clay Soil.

Parameter	IEE Std 142-2007 [24]	Tool’s Results	% Error
w=22%	90.00	88.78	1.35
w=24%	80.00	85.37	6.7
w=20%	100.00	92.19	7.81
T=10°C	80.00	83.75	4.68
T=20°C	70.00	62.91	10.13
T=30°C	60.00	49.38	17.7

In the analysis of Wilcoxon Signed Rank test, the value of asymptotic significance (p-value) was observed. Hence, two hypotheses were made; null hypothesis (H_O) and alternate hypothesis (H_A). H_O is the hypothesis that indicates 'Tool Value = Standard Value', whereas H_A signifies 'Tool Value ≠ Standard Value'. In order to reject H_O, the value of asymptotic significance must be lower than the level of significance, which is 0.05. In other words, to reject H_O , the condition is: p-value < 0.05.

As portrayed in Fig. 12, the statistical outcomes revealed that the p-value of clay was 0.249 (p-value > 0.05). Thus, it can be concluded that the asymptotic significance (p- value) fails to reject the null hypothesis (H_O).



Test Statistics[a]

	VAR00004 - VAR00003
Z	-1.153[b]
Asymp. Sig. (2-tailed)	.249

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

Fig. 12. Screenshot of the test results in comparing the standard value with the estimated value of Clay.

VI. CONCLUSION

Even though the current methods for testing soil resistivity (e.g., Wenner) appear to yield the highest accuracy, the methods are tedious, costly, and time consuming. Hence, it is imminent to devise a simple and reliable calculator that estimates this value. The validation results revealed that the developed calculator is indeed reliable and may function as a significant application in near future. Future studies may take the initiative to explore more areas of parameters that affect soil resistivity with regression models untapped in this research, such as the impact of salt content. Hence, comprehensive and more accurate soil resistivity estimation can be made. Due to the limited dataset availability, only results from the tool for clay soil had been compared in this present project. Tests for other soil types should be performed by incorporating different parameters for validation of outcomes.

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