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Modeling of Petrophysical Relationship of Soil Water Content Estimation at Peat Lands

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Abstract: Estimating Soil Water Content (SWC) for peat soil is fundamental parameters that are essential for quality of soil especially during drying periods. Transformations and subsequent losses to groundwater or atmosphere are mediated by moisture conditions in the soil. Success or failure of food, fiber, and energy production from agricultural crops depends on soil water storage between rainfall and/or irrigation events. Despite this importance, predicting soil water dynamics especially during dry and wet season remains a major challenge in hydrology, environmental science, agriculture, and engineering. Hence this study aims to determine the mathematical model for the site-specific of petrophysical relationship for wet and dry season between dielectric permittivity and water content of the peat soil. Field survey measurements and laboratory measurements were conducted at peat soil area. Soil samples were collected from 0 to 1.0m layer for 20 point. Dielectric permittivity values were determined using 2D adjusted of parallel plate capacitor. The oven-drying process was conducted for soil water content estimation. Linear and polynomial models were adjusted for the peat soil between dielectric permittivity and water content. From the results shows that the modeled of site-specific of petrophysical relationship gives better correlation for dry season (R^2=0.9812) and wet season (R^2=0.9441). The comparisons of GPR-derived estimates of water content to gravimetric measurements showed that GPR measurements using the modeled site-specific petrophysical relationships for both season had a root mean square error of 0.017 (wet season) and 0.25 (dry season). This indicates that the modeled equations can be used to estimate the water content of the peat soil when measured it by using GPR. Besides, through verifying the model of site-specific of petrophysical relationship using ground penetrating radar (GPR) along with three proposed model (Roth equation, Schaap equation and Idi equation) where the season was taken as consideration, the adjusted models provide sufficient accuracy to determine soil water content of peat soil for wet and dry season.

Keywords: Petrophysical relationship, Dielectric permittivity, Soil water content, Peat soil.

1. Introduction

Peat soil is an important ecosystem (Adon et al. 2013) and plays as a natural fertilizer that can improve the quality of the soil. Hence, the information about the properties of peat soil needs to be fully understood. The complex behavior of the petrophysical properties of peat soil, especially in terms of the quality of the soil, necessitates extensive research for an understanding of the behavior of these properties. Water content is one of the properties that can influence soil quality. Kaiser et al. (2010) mentioned that water presence more in organic soils than mineral soils and clearly making it possible for SWC estimation. Indeed, water is the component that has the greatest influence on the apparent dielectric permittivity (81). This is because, since water contains ion and the electrical conductivity associated with ion mobility is the dominant factor in determining bulk material electrical conductivity. Besides, as water presents in pore space

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naturally, it has dominant effect on electrical properties. The dielectric permittivity is able to store energy and the electromagnetic (EM) waves will be released in the form of electric charges (Senin & Hamid 2016). Soil with a low water content leads to deeper penetration in the vegetation and soil. This is due to the variability of the dielectric permittivity of the soil in the presence of water. To determine the soil water content (SWC) of peat soil in Malaysia, a suitable site-specific petrophysical relationship for peat soil is needed between two parameters (i.e., the dielectric permittivity and the water content of the soil).

To model the petrophysical relationship of dielectric permittivity -water content, important issues and factors need to be considered, such as:

1. Scale dependency of the dielectric permittivity-water content
2. Operation frequency
3. Required measurements accuracy
4. Material/subsurface properties

The scale dependency of the relationship of the dielectric permittivity-water content determines how small-scale petrophysical relationships (Time-domain reflectometry (TDR), neutron probe) relate and can be applied in a field-scale relationship (e.g., Ground penetrating radar) to interpret data for SWC estimation. In this study, one of the factors that needs to be considered is the operation frequency. The frequency selected for calibration parameters needs to be considered as it can affect the required accuracy of the measurements (Karim et al. 2018). For example, previous researchers used TDR as the calibration method with a low frequency as it does not affect the dielectric permittivity. However, when TDR applies a higher frequency for the measurements, the dielectric permittivity becomes increases. Hence, in this study, a site-specific model of the petrophysical relationship is modeled to determine the water content of peat soil, specifically in Malaysia. This study is conducted to provide better accuracy for the soil water content in areas with peat soil using the capacitance based-method.

2. Theory of Petrophysical Relationship

Previous researchers have provided a few petrophysical relationships between the dielectric permittivity (ε) and the water content (θ). The petrophysical relationship of the SWC estimation can be categorized between one parameter (e.g., dielectric permittivity) and two parameters (e.g., dielectric permittivity, conductivity, porosity). The theoretical approaches mostly frequently relate to the use of the dielectric permittivity-water content relationship (Mukhlisin & Saputra 2013), such as the Topp equation, Roth equation, Schaap equation and many more. The most commonly applied petrophysical relationship for SWC estimation is an empirical equation, such as the Topp equation (Topp et al. 1980):

$$\theta = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_r - 5.5\times10^{-4}\varepsilon_r^{2} + 4.3\times10^{6}\varepsilon_r^{3} \quad (1)$$

The parameters involved in this empirical equation have been proven to satisfy the measurement of mineral soils with acceptable accuracy. Unfortunately, when applied in organic-rich soils (e.g., peat) the signals tend to deviate from this relationship. However, it should be noted that a few researchers have made significant advancements in modeling a site-specific petrophysical relationship for organic soil. Various empirical relationships have been modeled by researchers, such as the Roth Equation (Roth et al. 1992), Schaap equation (Schaap et al. 1997), Pumpanen and Illveniem (Pumpanen & Ilvesniemi 2005), Parsekian and Slater (Parsekian et al. 2012), and many more. The researchers used a variety of calibration methods to model the dielectric permittivity determination, such as time domain reflectometry (TDR), capacitance, and a parallel-plate capacitor. Considering several factors for calibrating the model for the site-specific petrophysical relationship, such as operation frequency, scale dependency, mineralogy, and many more has led to different levels of accuracy with the results ranging considerably, especially when estimating the SWC. Roth et al. (Roth et al. 1992) proposed a $\varepsilon - \theta$ relationship using TDR as the calibration method for several types of soil (i.e., mineral soil, organic soil, and magnetic soil) with the prediction error for mineral soil and organic soil being 0.015 $cm^{3c}m^{-3}$ and 0.035 $cm^{3c}m^{-3}$, respectively. The site-specific petrophysical relationship is as follows:

$$\theta = -0.0233 + 0.0285\varepsilon - 0.00431\varepsilon^2 + 0.0304\varepsilon^3 \quad (2)$$

A simple equation proposed by Schaap et al. (Schaap et al. 1997) also used TDR as the calibrating method with 505 measurements from an organic forest sample. The equation is as follows:

$$\theta = 0.136\sqrt{\varepsilon} - 0.119 \quad (3)$$

Idi et al. (Kamarudin 2013) proposed the $\varepsilon - \theta$ relationship based on the third order polynomial with 36 measurements from peat soils using permittivity based on the capacitance measurements collected at Pontian, Johor Bharu. The equation is as follows:

$$\theta = -0.15943 + 0.1326\varepsilon - 0.0038\varepsilon^2 + 0.000036\varepsilon^3 \quad (4)$$

where,
θ= water content
ε= dielectric permittivity

3. Materials and Method

Field measurements consist of GPR survey measurements and soil sampling activity. Both measurements activities were conducted at rich peatland field location Olak Lempit, Banting Selangor. The Ground Penetrating Radar (GPR) survey measurements were conducted using GPR of IDS DuoDetector (i.e. 250MHz and 700MHz). From the frequency, depth penetration and resolution can be determined through the results. As the frequency increases lead to better resolution but lower depth penetration. Jol & Smith (1995) reported that low frequency antenna lend themselves the best measurements for peat soil while higher frequency gives data on near surface layers and moisture differences between peat layers (Finnish Geotechnical Society, 1992). The GPR components consist of transmitter, receiver and antenna frequency. The setting of the GPR controlled by computer before, during and after the survey measurements. Common-Offset Measurements method for GPR measurements were used to estimate the SWC of the peat soil. Further investigation of the ability of this method the field survey measurements was conducted using dual frequencies for SWC estimation. The GPR survey measurements were conducted in east-north direction with longitudinal and transversal direction. Figure 1 depicts the diagram for GPR measurements survey on field and the number labeled on each box represents the point for soil samples to be taken.

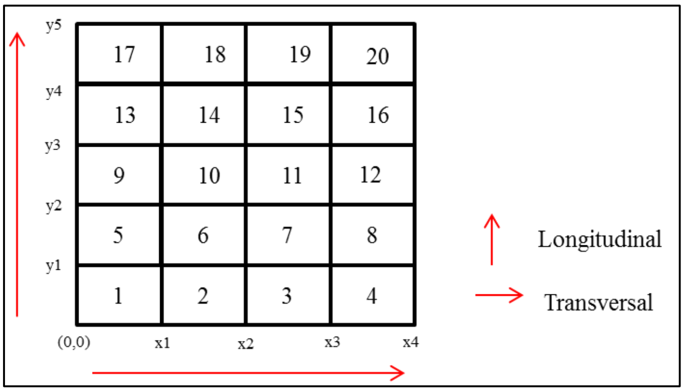


Fig 1 Grid Line of GPR Measurements

Soil sampling activity was conducted after the scanning profile using GPR. Figure 2 illustrates the soil sampling activity were conducted on peat soil. Firstly, for the sampling activity, the sampling area was defined. Once the area has been defined, mark them on the map before the sampling activity is begun. Label the sampling point with name or number and mark the corresponding samples containers or plastics before heading for sampling. The number of samples needed is determined per field. In this study, 20 samples were taken for two laboratory purposes. The number of sample id dependent upon the amount of variability within the field. There are some factors need to be considered for soil sampling activity such as; soil types and textures, slopes of the field, cropping history, manure history, drainage and erosion. Then, properly collect the samples for each points and depths. Using suitable tools such as soil probe or soil auger to collect the samples at a grid pattern and making sure that the sampling area is adequately represented. During the sampling, be sure to void scoping any crop residue and manure off of the soil surface.

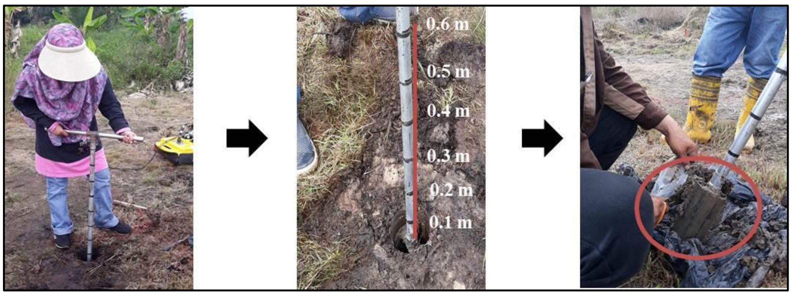


Fig 2 Soil sampling activity

Laboratory measurements consist of oven-drying method and capacitor- based measurements. These two methods were conducted at two different laboratory using the samples taken from the sampling activity. These two measurements were then will be used to model the site-specific of petrophysical relationship between soil water content and dielectric permittivity parameters. To assess the ability of GPR common-offset measurements method, gravimetric measurement was conducted. The experiments was undergo at Civil Engineering Laboratory (Soil laboratory) to obtain mass of the soil samples. This activity was monitored by assistant of engineer throughout the experiments was conducted. For SWC estimation of peat soil, American Society for Testing and Materials (ASTM) (ASTM 1990) experimental standard was referred. For dielectric permittivity determination, capacitor based-method was used for peat soil. A 2 dimensional (2D) adjusting soil cylindrical capacitor was designed for this parameter determination.

4. Model descriptions

Modeling the site-specific petrophysical relationship between the dielectric permittivity and water content was conducted using laboratory measurements by means of the parallel-plate capacitor-based method (dielectric permittivity determination) and the oven-drying method (water content estimation). Two-hundred samples of peat soil were taken for laboratory measurement. To determine the dielectric permittivity, a two-dimensional (2D) adjustable soil cylindrical capacitor was designed and fabricated to obtain the capacitance measurements. The capacitance measurements were then converted to dielectric permittivity using various equations. To estimate the water content, the oven-drying measurement was conducted in the soil laboratory for each sample taken from different depths. This method is a standard method of measuring soil water content, which is based on the loss of mass after a soil sample has been oven dried for a specified period of time. The dielectric permittivity and water content were modeled using the regression model. The modeled petrophysical relationship was then used to estimate the SWC of peat soil in Malaysia.

4.1 Determination of Dielectric Permittivity

The capacitance-based method was used in the experiment to determine the dielectric permittivity. The soil cylindrical capacitor model was designed to determine the dielectric permittivity of the peat soil. Twenty-three samples were taken for the experiments. A two-dimensional adjustable soil cylindrical capacitor model was built using transparent polylactic acid (PLA) plastic, food grade silicon sheets, and 6061-grade aluminum plate. Figure 3 displays the two-dimensional (2D) adjustable soil cylindrical capacitor model, which a customized design model is built by 3D Synapsis Sdn Bhd. Circular plate of 0.041mm diameter was cut from the aluminum plate. An electrically conductive soldering gun was used to solder a copper lead on one side of the plate to serve as the current lead, while silicon material was cut into the shape of a disc of the same diameter as the aluminum plate to serve as a rigid support to the plates. The plates were placed in parallel inside a plastic cylinder of the same internal diameter so that with the support of the silicon plate, they could be positioned at the desired separation.

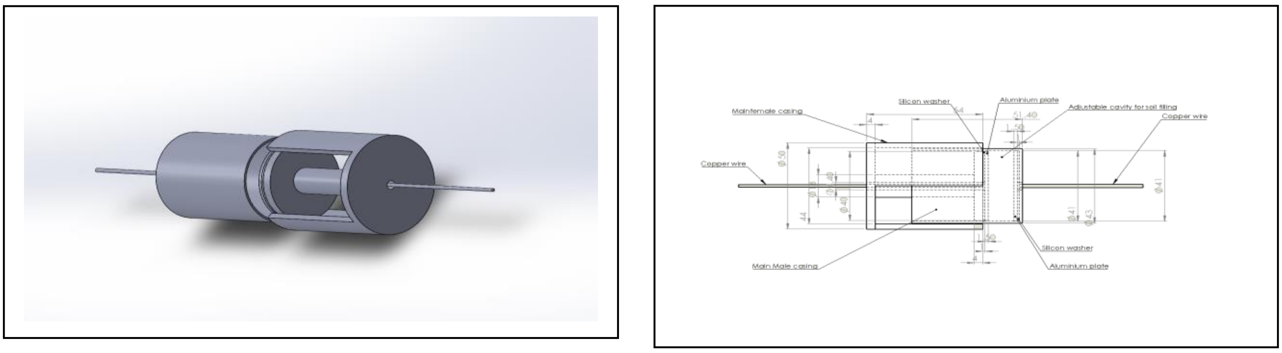


Fig 3 Two-Dimensional Adjustable Soil Cylindrical Capacitor

An electrical circuit was used to measure the capacitance of the capacitor with space between the plates and then with the sampled soil as the dielectric medium. The circuit components consist of a high-frequency variable signal generator, high sensitive digital alternating current (a.c.) micro ammeter, an a.c. voltmeter and connecting leads. The experiment was firstly conducted by measuring the dielectric permittivity of the air. This was accomplished by connecting the setup with air or free-space between the parallel plates. After few trials, it was observed and concluded that an appreciable response was obtained at a signal frequency of 1MHz. This frequency was chosen for the experiment as the current in the circuit is too low to be accurately recorded at a higher frequency.

4.2 Water Content Estimation

The laboratory measurements for SWC estimation, the American Society for Testing and Materials (ASTM) (ASTM 1990) experimental standard was used. According to the standard, the water content may be expressed by weight as the ratio of the mass of water present to the dry weight of the sample of soil. To obtain the water content of the soil, the water mass was determined by drying the soil to a constant weight and measuring the mass of the sample of soil before and after the drying process. The difference between the mass of the wet and dry samples is the weight of the soil. The samples were taken using a hand auger sampler at different depths for the two laboratory experiments. Samples weighing approximately 50 g were put in a plastic specimen jar and sealed with plastic tape. Each sample was identified by the code. The samples were then dried using the oven drying method at 105ºC for 24 hours. The moisture content was calculated using the following formula:

$$\mathrm{MC} = \frac{W_2 - W_1}{W_3 - W_1} \times 100\% \tag{5}$$

W_1 = weight of empty container
W_2 = weight of wet soil + container
W_3 = weight of dry soil + container

5. Results and Discussions

According to Idi (2013) and Nagare et al. (2011), the relationship between the water content and dielectric permittivity as been described as the most accurate means of correlation. The simplest approach to estimate the soil water content estimation, is by developing regression equation of site-specific petrophysical relationship. This relationship is usually based on data peat soil and land use conditions and generally can be extrapolated from one location to another . Previous researcher have presented an exprressions form for a regression equations to estimate SWC at deeper layers. In this work, the SWC estimation in one-metre depth layer was measured and determine using two parameter model of the moisture profile. The first parameter model was the moisture content from the peat soil of the 0-10 cm soil layer determined by the gravimetric measurements method. The second parameter was the electrical properties, dielectric permittivity of peat soil profile in the field using apacitor-based method.

5.1 Model Fitting of the Site-Specific Petrophysical Relationship (Dry Season)

$$y = \beta_o + \beta_1 x + e \tag{6}$$

The parameters β_o determines the intercept and the slope of the line respectively. The intercept β_1 represents the predicted value of y when x= 0. The slope β_1 represents the predicted increases in Y resulting from a one unit increases in x.

Table 1 Summary Output of Model of Site Specific of Petrophysical Relationship (Dry Season)

Type of regression	Significant F	Standard error	R^2
Linear model	2.89851X10-6	0.6418	0.6052
Second –order polynomial	1.88E-14	0.2641	0.9072
Third-order polynomial	4E-19	0.1463	0.9812

Table 1 illustrates the summary of three models of site-specific of petrophysical relationship at peat soil for wet season. As simple linear regression analysis was computed based on this model with the results from the experimental measurements (dielectric permittivity determination and water content estimation) as inputs.it could be observed that the goodness of fit linear model is R^2=0.6052. This shows that 60% of the variation of water content,θ is attributed from dielectric permittivity, ε_r. Even though the relationship shows good relationship between the variables, however, the fitting parameter appears to be relatively less scattering of the point shows in the regression line. The second-order polynomial suggests the relationship between water content, θ and dielectric permittivity, ε_r and is defined as:

$$\theta_j = \alpha + \beta\varepsilon_r + \gamma{\varepsilon_r}^2 + e_j \tag{7}$$

From the model can be concluded that, the goodness of fit is R^2=0.9072 which indicates that 90% of confidence level of predicting the equation. From this results shows that there is improvements in the goodness of fit as shown in figure 4 (b) compared to the simple linear model in figure 4 (a). Besides, the model suggests third-order polynomial and is defined as:

$$\theta_j(\varepsilon_r) = \alpha + \beta\varepsilon_r + \gamma{\varepsilon_r}^2 + \gamma{\varepsilon_r}^3 + e_j \quad (8)$$

Figure 5 shows the plotting graph of the best fit model for the SWC estimation. The goodness of fit from the model output summary shows for this model is R^2= 0.9812 which implies 94% of the variation in water content, θ is attributed to dielectric permittivity, ε. Out of all the three models, this model outperforms the remaining three in the goodness of fit.

To test the null hypothesis, F-test statistics is computed, which is the coefficient value is equal to 0 (no effect). Low p-value (<0.05) indicates that the null hypothesis can be rejected. Based on the findings, a corresponding P-value of 2.89851×10^{-6} for linear model, 1.88E-14 for second –order polynomial and 4E-19 from third order polynomial where all the results given is (<0.05) implies that H(0) is rejected at 0.05/5% level of significance. In other words, a predictor that has low p-value is likely to be meaningful addition to the model as the changes in the predictions value are related to change in the response variable.

(a)

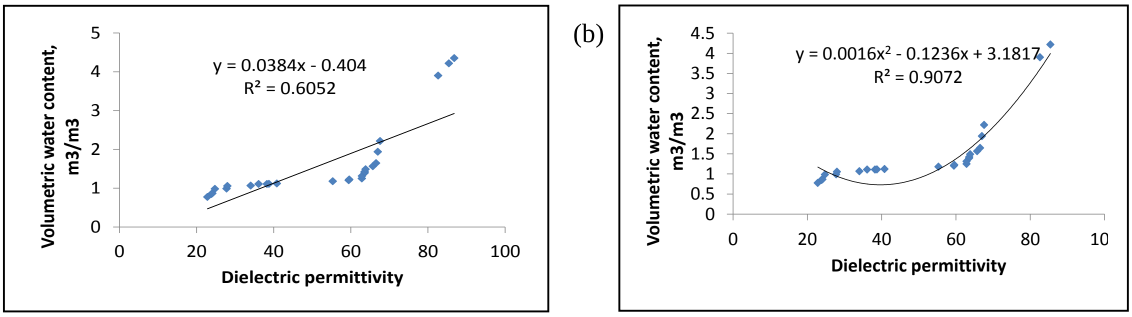


Fig. 4 (a) Line of fit of linear model; (b) line of fit of Second-Order polynomial

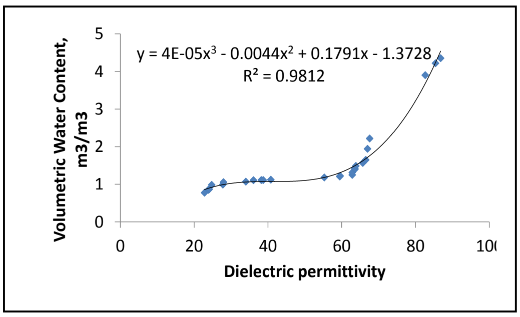


Fig. 5 Line of fit Third Polynomial

Based on the results, the third-order polynomial was modeled from the measured data. The equation provides good accuracy for the coefficient of determination with R^2= 0.98, N-23 to determine the water content of peat soil at the 98% confidence level.

Table 2 Model Summary

Type of regression	Equation	R^2
Linear model	$\theta = 0.038\varepsilon_r - 0.404$	0.6052
Second-Order Polynomial	$\theta = 0.0016{\varepsilon_r}^2 - 0.1236\varepsilon_r + 3.1817$	0.9072
Third-Order Polynomial	$\theta = 4 \times 10^{-5}{\varepsilon_r}^3 - 0.0044{\varepsilon_r}^2 + 0.1791\varepsilon_r - 1.3728$	0.9812

5.2 Model Fitting of the Site-Specific Petrophysical Relationship (Wet Season)

$$y = \beta_o + \beta_1 x + e \tag{9}$$

The parameters β_o determines the intercept and the slope of the line respectively. The intercept β_1 represents the predicted value of y when x= 0. The slope β_1 represents the predicted increases in Y resulting from a one unit increases in x.

Table 3 Summarize of Model of Site Specific of Petrophysical Relationship (Wet Season)

Type of regression	Significant F	Standard error	R^2
Linear model	2.14E-07	0.147149	0.6299
Second –order polynomial	1.41E-08	0.133181	0.738
Third-order polynomial	2.1E-16	0.06266	0.9441

Based on Table 3 illustrates the summary of three models of site-specific of petrophysical relationship at peat soil for wet season. As simple linear regression analysis was computed based on this model with the results from the experimental measurements (dielectric permittivity determination and water content estimation) as inputs.it could be observed that the goodness of fit linear model is R^2=0.6299. This shows that 63% of the variation of water content,θ is attributed from dielectric permittivity, ε_r. Even though the relationship shows good relationship between the variables, however, the fitting parameter appears to be relatively less scattering of the point shows in the regression line. The second-order polynomial suggests the relationship between water content, θ and dielectric permittivity, ε_r and is defined as:

$$\theta_j = \alpha + \beta\varepsilon_r + \gamma{\varepsilon_r}^2 + e_j \tag{10}$$

From the model can be concluded that, the goodness of fit is R^2=0.738 as shown in Fig 6 (b) which indicates that 73.8% of confidence level of predicting the equation. From the results shows there is improvements in the goodness of fit of the model compared to the simple linear model shown in figure 6 (a). Besides, the model suggests third-order polynomial and is defined as:

$$\theta_j(\varepsilon_r) = \alpha + \beta\varepsilon_r + \gamma{\varepsilon_r}^2 + \gamma{\varepsilon_r}^3 + e_j \tag{11}$$

Figure 7 shows the plotting graph of third-order polynomial of site-specific petrophysical relationship (wet season). The goodness of fit from the model output summary shows for this model is R^2= 0.9441 which implies 94% of the variation in water content, θ is attributed to dielectric permittivity, ε. Out of all the three models, this model outperforms the remaining three in the goodness of fit.

To test the null hypothesis, F-test statistics is computed, which is the coefficient value is equal to 0 (no effect). Low p-value (<0.05) indicates that the null hypothesis can be rejected. Based on the findings, a corresponding P-value of 2.14 × 7 for simple linear model , 1.41E-08 for second order polynomial and, 2.1E-16 for third order polynomial (<0.05) implies that H(0) is rejected at 0.05/5% level of significance. In other words, a predictor that has low p-value is likely to be meaningful addition to the model as the changes in the predictions value are related to change in the response variable.

(a) (b)

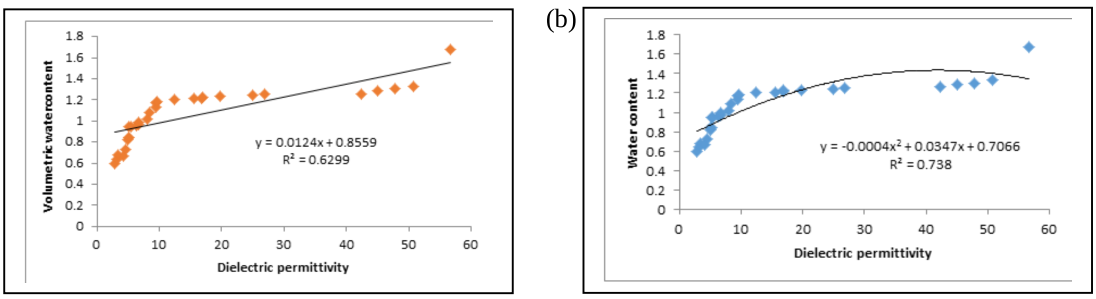


Fig 6 (a) Simple Linear Model; (b) Line Fit of Second-Order

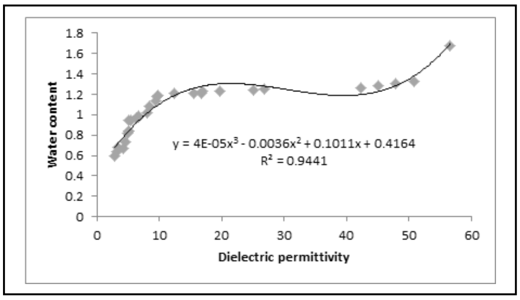


Fig 7 Line Fit of Third-Order

Table 4 Model summary

Type of regression	Equation	R^2
Linear model	$\theta = 0.0124\varepsilon + 0.8559$	0.6299
Second-Order Polynomial	$\theta = 0.0004{\varepsilon_r}^2 + 0.0347\varepsilon + 0.7066$	0.758
Third-Order Polynomial	$\theta = 4 \times 10^{-5}{\varepsilon_r}^3 - 0.0036{\varepsilon_r}^2 + 0.1011\varepsilon_r + 0.4164$	0.9441

To develop site-specific of petrophysical relationship expression, a simple linear regression was applied for the dielectric-permittivity-water content relationship values from a combined data set of measurements exhibited more scatter than the single result shown in Table 2 and table 4, a linear rather than higher order regression were employed. The resulting of both relationships is as follows:

Dry Season:

$$\theta = 4 \times 10^{-5}{\varepsilon_r}^3 - 0.0044{\varepsilon_r}^2 + 0.1791\varepsilon_r - 1.372 \quad (12)$$

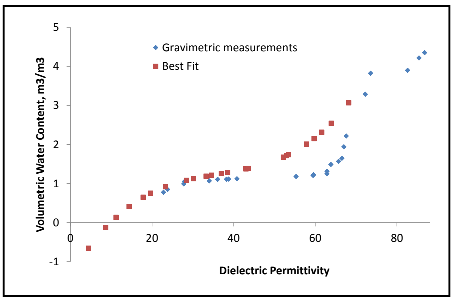
Wet Season

$$\theta = 4 \times 10^{-5}{\varepsilon_r}^3 - 0.0036{\varepsilon_r}^2 + 0.1011\varepsilon_r + 0.4164 \quad (13)$$

Significantly, previous researchers, such as Slater and Steelman (Steelman & Endres 2011), provided similar results to those obtained in this study. To model the site-specific petrophysical relationship between the dielectric permittivity and the water content, several factors that contribute to the electrical properties of the dielectric permittivity, and, hence, affect the accuracy of the equation to predict need to be considered. According to Idi et al. (Kamarudin 2013), the dielectric permittivity is complex, and frequency-dependent, especially when water is present. In soils, the dielectric permittivity can have a greater effect than magnetic permeability and electrical conductivity (Rehman et al. 2016). Topp et al. (1980) reported that at frequencies below 1GHz, dielectric permittivity is only weakly frequency dependent, but increases rapidly with increasing frequency. This statement is supported by Idi et al. (Kamarudin 2013) who found that this is because at certain frequency ranges (e.g., .1MHz to 1GHz), the dipolar molecules of water content have the greatest influence on the dielectric permittivity of peat soil, and, hence, dielectric permittivity is therefore nearly constant within this range. In addition, Curtis (Tobergte & Curtis 2013) also measured the dielectric permittivity using coaxial transmission and a frequency of 100MHz. The results show that the SWC measurements are dependent on the signal frequency with a potential 10% under prediction of the volumetric water content using the equation with frequencies of 500MHz and 1000MHz with higher permittivity (e.g., $k \geq 30$).

6. Validation of the relationship between the variables and gravimetric measurements

(a)



(b)

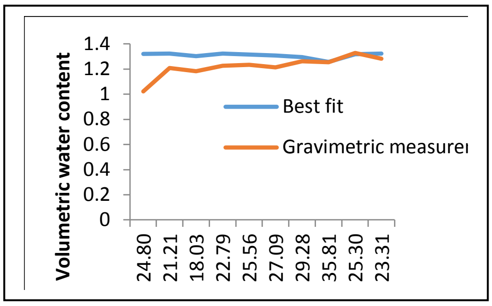


Fig 8 GPR Permittivity with corresponding volumetric water content with data superimposed with our best fit third-order polynomial and gravimetric measurements for (a) dry season and (b) wet season

The accuracy of the site-specific petrophysical relationship between the dielectric permittivity and the water content of the soil was tested using the data interpretation procedure. The water content estimates from the GPR measurements were compared with the volumetric water content obtained from the gravimetric measurements collected from 0-10cm depth in the middle of each GPR line as a bench mark. Figure 8 (a) shows the graph for the GPR permittivity corresponding to the volumetric water content with the data superimposed with our best fit model and gravimetric measurements. The plotting graph shows that the model is agree well with gravimetric measurements. Clearly, there is a good general agreement between both model (dry and wet season) since they show the similar patterns in soil water. By using the 250 MHz antenna frequency, the models generally found similar trends in soil water content estimated with Ground Penetrating Radar (GPR) survey measurements with common-offset measurements and reference small scale measurements. The accuracy of the measurement data was determined using the root mean square error (RMSE), which gives a low RMSE of 0.017 for dry season and 0.025 for wet season.

The possible reason for the differences between the field measurements and laboratory measurements might be due to inaccuracies in the density estimates used to convert the gravimetric measurements to the volumetric water content. However, despite the possible reason for the error, the RMSE for the third-order polynomial is very small, and the accuracy of the SWC estimates is sufficient for SWC for typical field applications.

7. Verification of Site-Specific of Petrophysical Relationship of Peat Soil

To verify the developed site-specific of petrophysical relationship, a second set of experiments was performed using the same procedure of water content estimation using GPR for the purpose of obtaining an independent prediction set and corresponding gravimetric measurements. By using the geophysical tool, Ground-Penetrating Radar (GPR) was used to verify the modeled fitting of the site-specific petrophysical relationship to estimate the SWC; common-offset measurements were applied on peat soil with gravimetric measurements. Field survey measurements were conducted at Olak Lempit, Banting Selangor (peat soil). Using dual frequency (e.g., 250MHz and 700MHz), nine profiles of length 8m x 10 m each were scanned along the east-west and south-north direction at an equal distance of 2 m. The results from GPR data were collected using a time window of 100 ns, sampling interval of 0.1 ns, and 64/stacks per trace. The velocity of the electromagnetic waves from the profile was determined to be converted to dielectric permittivity for water content estimation. Basic processing is needed to obtain good results for the radargram profile before computation of the parameter can be determined. Cassidy (Cassidy 2009) stated that the maintenance should be taking care to obtain good results. Hence, in this study, some basics processing (i.e. dewow filtering, gain functions, background removal, and static corrections) were applied.

Gravimetric measurement (oven-drying) is an accurate standard method with an accuracy of (+-0.01ft^3ft^{-3}) was conducted for validation with the GPR measurements data. This method has been extensively used by previous researchers when validating other methods of calibration. In this study, 20 samples were collected over a half-meter of peat soil at depth intervals of 0.1 meter for the experimental measurements. Oven-drying process was conducted to extract the volumetric water content of peat soil at 105^o C for 24 hours in the soil laboratory. The water content was determined by extracting a known volume of soil using small aluminum cylinders and measuring their mass using equation (5). Three existing site-specific petrophysical relationships (i.e., Roth equation, Schaap equation, and Idi equation) were used to verify the trend line of the best fit third-order polynomial for both seasons.

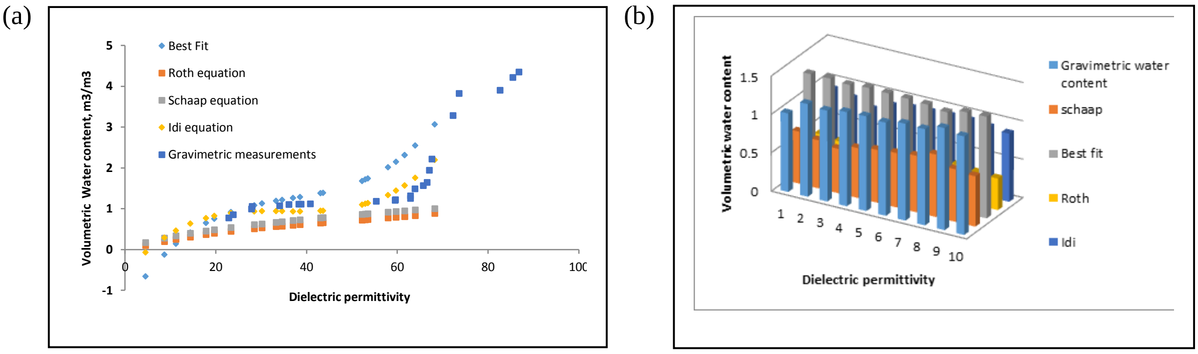


Fig 9 GPR Permittivity with corresponding volumetric water content with data superimposed with petrophysical relationship proposed by Roth et al. (1992), Schaap et al. (1997) and Kamarudin (2013)

To examine the suitability of the established petrophyscial relationship (Roth model, Schaap model and Idi model), we have superimposed the equations on plots of the dielectric permittivity of the peat soil and field water content in Figure 9 (a) and (b). Based on the plotting graph for dry season at figure (a), best fit model resulted in the most accurate predictions for volumetric water content of peat soil (RMSE=0.12). The standard petrophyscial relationship proposed by Roth et al. (1992), Schaap et al. (1997) predict relatively lower water contents in comparison with gravimetric measurements. The model proposed by Kamarudin (2013) yields a much better fit to these data compared with those obtained with Roth and Schaap model. Figure 9 (b) shows the GPR results for water content-dielectric permittivity relationship are plotted for wet season. The best fit model gave the most accurate predictions for the relationship between dielectric permittivity and water content (RMSE=0.26) while the least predictions obtained by model proposed by Roth (Roth et al. 1992). The model proposed by Idi ((Kamarudin 2013) provides better fit that Roth model. While Idi model provide better fit for the results, the Schaap model significantly slightly under predict the soil water content data.

8. Conclusion

Soil water content estimation is important in various field especially agriculture, soil science and climatology. However, appropriate petrophysical relationship is needed to estimate the water content especially on peat soil when using GPR as a measurements tool. Since water presence in the soil, it has dominant effect on electrical properties such as dielectric permittivity. The relationship between dielectric permittivity and water content to model the site specific of petrophysical relationship to estimate water content of peat soil shows great correlation. The models from (Roth et al. 1992),(Ferre et al. 1998), (Kamarudin 2013) shows less estimated when estimating water content on peat soil. Best fit third-order polynomial was modelled to estimate the water content on peat soil. The results shows better accuracy when validate with gravimetric measurements for both model (dry and wet season). To model the site-specific petrophysical relationship, frequency is one of the factors that affect the accuracy of the results. The best fitting relationship de exhibit some degree of textural bias that should be considered in the choice of petrophysical relationship for a given measurements. In this study, the proposed model incorporated the characteristics into it and provides the data better than the established models. Our models of site-specific of petrophysical relationship have shown that the GPR measurements cab be used to estimate the water content when using the modelled equations with a RMSE of 0.017 for dry season and 0.25 for wet season. The modelled equations have better accuracy for both seasons when compared it with the existing equations. This indicates that the proposed model has more extensive suitability for the site specific especially peat soil in Malaysia than the reported models and suggest that the model parameters may also have more fundamental physical meanings. Our study marks the first attempt to provide the models that gives better accuracy in determining the water content of the peat soil for dry and wet season.

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