Soil water content estimation at peat soil using GPR common-offset measurements

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Abstract. The appropriate of petrophysical relationship is needed for Soil Water Content (SWC) estimation especially when using Ground Penetrating Radar (GPR). Ground penetrating radar is a geophysical tool that provides indirectly the parameter of SWC. This paper examines the performance of few published petrophysical relationships to obtain SWC estimates from in-situ GPR common- offset survey measurements with gravimetric measurements at peat soil area. Gravimetric measurements were conducted to support of GPR measurements for the accuracy assessment. Further, GPR with dual frequencies (250MHz and 700MHz) were used in the survey measurements to obtain the dielectric permittivity. Three empirical equations (i.e. Roth's equation, Schaap's equation and Idi's equation) were selected for the study, used to compute the soil water content from dielectric permittivity of the GPR profile. The results indicate that Schaap's equation provides strong correlation with SWC as measured by GPR data sets and gravimetric measurements.

1. Introduction

Soil water content plays important role in various environmental studies such as hydrology, agriculture, ecology and many more. For instance, in the application of agriculture, SWC is importance for optimizing crop yield especially in peat soil area. The measurements of SWC have made great contributions to variety of field. Soil water content estimation can be estimate using few methods. Direct method is a method where the parameter of SWC will straightly provide the value of water content either through laboratory or field survey. Gravimetric sampling method has been employed as a standard method which is one of the direct methods that provide information of the water content through oven-drying process. This method ensures the accurate result as it does not concern and depends on the soil salinity and soil type. In this technique, the soil samples will be oven-drying for 24 hours at 105^{o}C which is time consuming. Besides, the samples cannot be used for repetitive measurements as its structure gets disturbed make it destructive method. Time Domain Reflectometry (TDR) is point measurements methods that have been commonly used by the researchers. This high temporal resolution method needs to use empirical equations to compute SWC of the soil such as Topp's equation [1]. However, highly in cost and limited in scale make it the researcher use other methods that are convenient for the larger scale and high resolution. Due to the limited in scale for SWC estimation, remote sensing is the most suitable for the researcher to estimate SWC at larger area [2] need to be covered on a repetitive basis uniformly. However, it is costly and complex. To be able estimate SWC from smaller scale to larger scale at higher resolution, Ground Penetrating Radar (GPR) is the most suitable SWC estimation measuring device.

Ground penetrating Radar (GPR) is a non-invasive [3] tool that uses high resolution frequency between 10-1000MHz lie in Electromagnetic (EM) theory. This geophysical tool [4] transmits EM pulse into the ground using antenna. The main parts in GPR are receiver, transmitter and control unit. Antenna of GPR is important for the signal detection and transmission from EM field. The heart of GPR is the timing unit which controls the generations and detection of signals. Details about the GPR fundamental can be found on [5] and [6]. This non-destructive method can estimate SWC from smaller scale to larger scale in a short time and high in resolution. Researcher [6] reported that GPR consist of two main aspects which are resolution and depth. As the resolution of the GPR is increases, the depth penetration will be less. Researcher [7] mentioned that it is better to trade resolution for depth, with high resolution being useless if the target cannot be detected. Furthermore, GPR reacts when the presence of water in the soil dominates behaviors. Since water presents in the pore space of natural (geologic) materials, it has dominant effect on electrical properties. Electrical properties of GPR consist of permittivity, electrical field and conductivity. The permittivity of the GPR is calculated using EM velocity of the signal detect of the subsurface. The SWC then will be determined by using the petrophysical relationships such as Topp's equation [1], Roth's equation [8] , Ferre's equation [9] and many more. Most of the researcher focus on developed the petrophysical relationship on mineral soil and only few of researchers that focus on organic soil such as peat soil.

The GPR survey consists of four modes of operation [6] (i.e. Common-offset measurements, Common mid-point, Groundwave and Borehole transillumination) for SWC estimation. Common-offset measurements [10] are commonly used by the researcher for SWC estimation. This survey keeps the distance between transmitter and receiver. The antennas are deployed in a fixed geometry (separation and orientation) and measurements made at regular station interval. Common Mid-Point Measurements (CMP) also one of the common survey measurements used by the researcher. The transmitter and receiver are moved apart at equal distance from a mid-location. Besides, researchers [11] evaluate the potential of GPR for SWC estimation using 225 MHz frequency and compared with Time Domain Reflectometry (TDR). Besides, other researchers [12] also applied this method for SWC estimation at vadose zone. They reported that GPR provide high resolution travel time data between four stratigraphic reflection events. Groundwave method is an antenna separation method [3]. This method is suitable in the upper layer of the soil [3]. However, researchers [6] reported that the poor understanding of the propagation of the GPR signal in the radar antenna subsurface system hampers the application of groundwave method for monitoring SWC estimation in detail. Unlike groundwave method, borehole method use travel time of the radar wave between point of known location to generate a 2D velocity image between borehole, which can be converted to dielectric permittivity and Volumetric Water Content (VWC) estimates. However this method is invasive and requires sophisticated data processing. In this study, Common-offset survey measurement was conducted to estimate SWC at peat soil area. The objectives of the study are to compare the performance of the established petrophysical relationship for SWC estimation. this paper presents results of the SWC from the GPR using three different petrophysical relationship with dual frequencies (i.e. 250 MHz and 700MHz) and compare it with gravimetric measurements.

2. Petrophysical Relationship

Geophysical tools such as GPR can help on understanding of peat soil stratigraphy and hydrogeology. GPR method has been extensively used in variety of field. Previous researchers (Warner et al., 1990; Pelletier et al., 1991; Poole et al., 1997) illustrate the potential of the method for identifying the properties of a peatland. Besides, Low (1985) and Theimer et al. (1994) claimed that GPR is effective because it can penetrate up to 10m in peatland, with a resolution of 10-15 cm. The method is effective as water content changes occur at important interfaces, causing measurable GPR reflections. Theimer et al. (1994) mentioned that significant reflectors within peat have also been identified and associated with local changes in moisture content. As the dielectric constant of peat is well known, depending on peat type, (Theimer et al., 1994), reliable estimates of the depth to reflectors within and at the peat are obtainable. On the other hand, Persekian et al. (2012) recorded the dielectric permittivity for different water levels on 4 peat soil collected at Caribou Bou, Maine, and USA using linear regression analysis. The linear empirical equation is being obtained but with different parametric coefficients in each case. Thus, the results proved that there is difference in dielectric permittivity and water content relationship.

Prediction of SWC on peat soil useful for variety of field such as agriculture, hydrology, and environment. SWC information important for agriculture for irrigation and crop quatlity maintenace. On the other hand, for hydrology, SWC is used for detrermining the rate and quantity of water movement in peat soil.In process of simulation of SWC, several methods can be used for the prediction measurement such as direct and in-direct method. Direct method such as gravimetric measurements, water content is determined by subtracting dry soil from wet soil sample weights. These methods is accurate, but time consuming. However these method has disadvantage, it still be used as calibration for other methods. For in-direct methods, electrical methods is being used, Researchers had wisely discussed in detail in many previous study, where the issues are about intruments,large scale and small scale. Some other methods such as capacitance probe used difference approach, by measuring the capacitance, it then will be converted to dielectric permittivity. From the previous study, can be seen that the information of dielectric permittivity plays important role as it can be used to estimate water content. Permittivity is the most common electrical properties that was used to measure the SWC. Estimation of SWC from previous model can be be categorized into one parameter and two parameter. One parameter is defined as where it involve dielectric permittivity and water content only. Meanwhile, two parameter can be described where it include other parameters such as bulk density or porosity. For example, Topp had develop a model. The model is:

$$\varepsilon = 3.03 + 9.3\theta + 146\theta^2 - 76.7\theta^3 \quad (1)$$

where ε is the dielectric permittivity and θ is water content of the soil. This measurement use TDR at a frequency 1 to 1000 MHz of several mineral soil. Topp was used a polynomial fitting to obtain the ε-θ relationship model. Researchers [1] had produced another equation for SWC determination and it was used by researchers until today. The equation is as follows :

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\varepsilon - 5.5 \times 10^{-4}\varepsilon^2 + 4.3 \times 10^{-6}\varepsilon^3 \quad (2)$$

There are some equation of SWC estimation for organic soil formed by other researchers. Years by years, researchers becomes focus to organic soil as it is different to other soil. Hence, the model is different. For example, Topp's equation is not suitable for organic soil as it tend to deviate from it [13]. This fact also has been reported by [14]. The difference betwen the dielectric permittivity and water content in organic soil compared to mineral soil is due to the difference in bulk density and surface area. Researchers [8] used miniprobe and TDR to form equations for mineral soil and organic soil. The equations are as follows :

Mineral Soil :

$$\theta = -0.0728 + 0.0448\varepsilon - 0.00195\varepsilon^2 + 0.0000361\varepsilon^3 \quad (3)$$

Organic Soil :

$$\theta = -0.0233 + 0.0285\varepsilon - 0.000431\varepsilon^2 + 0.00000304\varepsilon^3 \quad (4)$$

They [8] also founds that the error estimation for mineral soil is 0.015cm^{3}cm^{-3} ,while for organic soil is 0.035m^{3}m^{-3}. Other researchers also provide SWC model. Researchers [9] used mixing model equations and TDR measurements to form an equation. The equation are as follows:

$$\theta = 0.1181\sqrt{\varepsilon} - 0.1841 \quad (5)$$

On the other hand, [15] choosed different approach compared to [9], where they formed a model for organic soil. These researchers, used 505 measurements from organic forest using TDR measurements. The equation is as follows:

$$\theta = 0.136\sqrt{\varepsilon} - 0.119 \quad (6)$$

Unlike other researchers, this researcher [16] use capacitance method to developed site specific petrophysical relationship. They used 35 samples of measurements form peat soil. The equation is as follows:

$$\theta = -0.5943 + 0.1326\varepsilon - 0.0038\varepsilon^2 + 0.000036\varepsilon^3 \quad (7)$$

Some other researchers developed an equation with two parameter either using bulk density or porosity. For example, some researchers,[17] form equation using porosity parameters.

$$\varepsilon = \theta\left(\varepsilon_i + (\varepsilon_w - \varepsilon_i)\frac{\theta}{\theta_t}\gamma\right) + (\eta - \theta)\varepsilon_0 + (1 - \eta)\varepsilon_r \quad (8)$$

$$= \theta_t(\varepsilon_i + (\varepsilon_w - \varepsilon_i)\gamma) + (\theta - \theta_t)\varepsilon_w + (\eta - \theta)\varepsilon_a + (1 - \eta)\varepsilon \quad (9)$$

where ε_i is permittivity for ice (3.2), ε_w is permittivity for water (80) and ε_r for rock (0.5). The first equationl is applied where $\theta \leq \theta_t$ while the second equation is applied where $\theta > \theta_t$. From the above equations for SWC, can be conclude that dielectric permittivity is vital important component for SWC model. Dielectric permittivity can be defined as the quantity that used to described dielectric properties that influenced reflection of EM waves at interfaces and the attenuation of wave energy within material. Dielectric permittivity capable to accumulate and discharge the EM energy that affecting EM wave propagation. Fay and Harris (2003) reported that the velocity of the EM waves depends on dielectric permittivity of material. Meanwhile, [18] mentioned that there is relationship between the velocity and dielectric permittivity for loss material. These statement is supported by some researchers [19]. The equation shows the relationship between velocity and dielectric permittivity:

$$\varepsilon = \left(\frac{C}{V}\right)^2 \quad (10)$$

where, ε i sthe dielectric permittivity, C is the EM velocity in free space and V is internal velocity.

3. Site Description

Study area was done on peat soil at Kuala Langat, Selangor. It is the most important peat swamp in south of the state of Selangor [20]. It is located at the west coast of peninsular Malaysia with an area 796084 hectares and consist of 9 regions and 55 districts. Land of Selangor is covered with peat swamp forest, forest plantation, forest land, palm oil, rice, rubber, coffee, cocoa, palm, thatch, tailings, terrain, villages and municipalities. It has uniform temperature between 21°C to 32°C. have high soil moisture and the amount of annual rainfall of about 2670 mm. Nearly 181,502 hectares or 23% of the land covered with peat soil, the rest is mineral soil. There are some factors need to be considered when choosing the study area. Factors such as accessibility, absence of external EM radiation, high tension cable need to be considered. This is because most of the peat soil area is waterlogged from the surface that makes it impossible for the scanner to pass through. Besides, the surveying measurements on high signal attenuation rate of radar energy may not be considerable success as large portions of energy will be reflected before reaching deeply into the peat deposit.

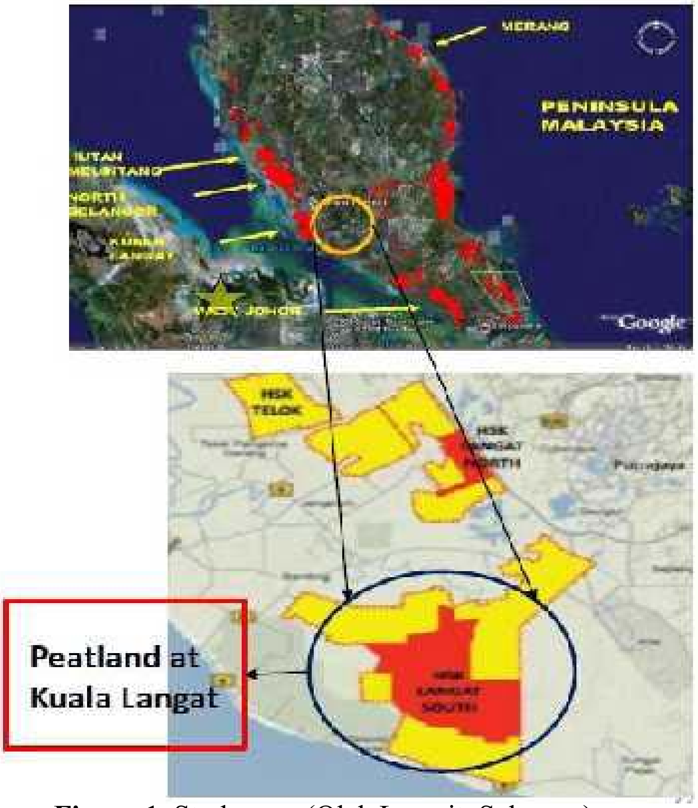

Figure 1. Study area (Olak Lempit, Selangor)

4. Data Acquisition

Common-offset reflection of GPR Survey measurements method is applied along a profile in a peat soil area to estimate SWC. The survey was deployed a single transmitter and single receiver, with a fixed and constant offset between the location. The survey involves by transmit the signal from the transmitter to receiver in a fixed antenna geometry over the surface in a repetitive steps. Several parameters involves in this survey measurements were time window, GPR central frequency, antenna spacing, antenna orientation, time sampling interval and station spacing. Soil water content estimation was conducted at peat soil area, located at Olak Lempit, Banting Selangor (coordinate) which is oil palm agricultural field. GPR measurements were conducted along a fixed survey line at the site using IDS (Ingegneria dei Sisteemi) Detector Duo shielded antenna with dual frequencies (250MHz and 700MHz). The 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 were determined to be converted to dielectric permittivity and then will be computed for SWC using appropriate petrophysical 6relationship. To obtain good results, the basic processing is needed for the radargram profile before the velocity of the waves is determined. Cassidy (2009) stated that it is important to obtain good results by taking care of the maintenance of the data. Here, it is proved that data editing (data processing) is needed for maintenance of the data. Hence, in this study, dewow filtering, gain functions, background removal and static corrections were applied to obtain good results.

Laboratory measurement was conducted to extract the volumetric water content on peat soil using oven-drying method. Oven-drying method or gravimetric measurements is a standard method which provide accurate results (+-0.01ft3ft-3) and has been extensively used by the researcher when validate with other methods such as GPR method and TDR. In this study, 200 samples were taken for the experiment. Samples were taken over the half meter of peat soil at 0.1 meter depth interval. Water content was determined by extracting a known volume of soil using small aluminium cylinders and measuring their mass after they were oven-dried at 105^{o} C for 24 hours in a soil laboratory.

5. Results and Discussions

This study represents the GPR common-offset measurements to estimate SWC at peat soil area. Dual frequencies 250MHz and 700MHz were used for the survey. Figure 3 and Figure 4 display the radargram of GPR profile for 250MHz and 700MHz across peat soil area, Olak Lempit, Selangor. The 250MHz reflection profiles provide deeper penetration than 700MHz. The 700MHz profiles provided high resolution information for the SWC information. The profile shows the reflections of the waves in two frequencies (deep and shallow). The hyperbolic fitting is marked with velocities fitted. The velocities from the hyperbolic fitting were converted to dielectric permittivity using equation (10) Where c=0.2998m/ns (velocity in air). The dielectric permittivity obtained then were used to compute the volumetric water content using established petrophysical relationships (i.e. Roth's equation; Schaap's equation; Idi's equation) equation that were chosen. The radargrams interpret that the water content was high at 3m depth. This result was then compared with the gravimetric sampling from the field.

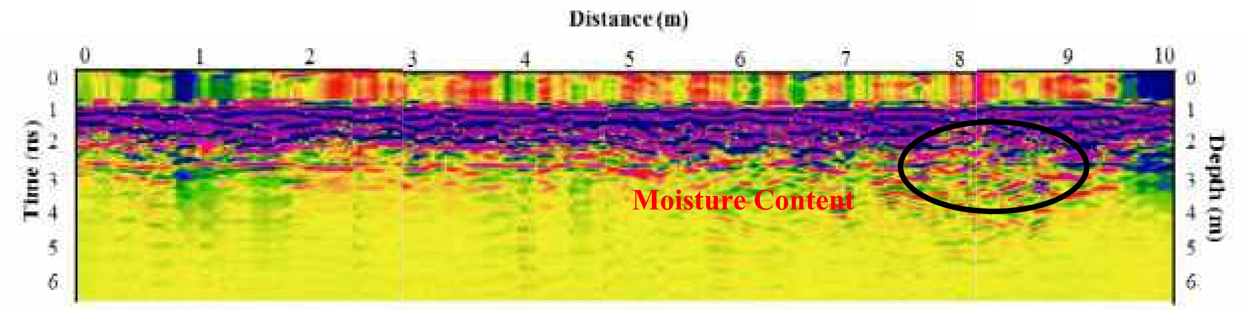

Figure 2. GPR Profile (250MHz)

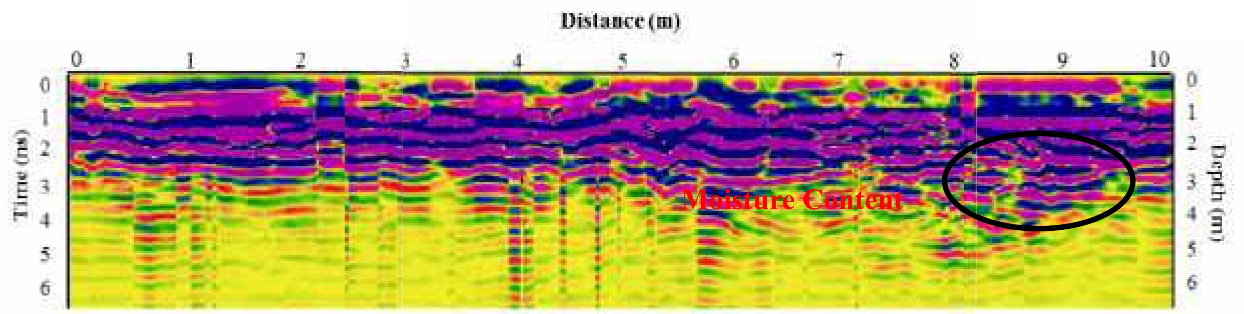

Figure 3. GPR Profile (700MHz)

Estimates of water content from GPR measurements from Roth's equation range from 0.399 to 1.071m^3m^{-3} and water content for Schaap's equation range from 0.6948 to 1.1753m^3m^{-3} while for water contents estimates from Idi's equation ranged from 0.9326 to 6.990m^3m^{-3}. To compare the accuracy of the GPR measurements, gravimetrcic measurements were taken and the water content ranged from 0.8656 to 1.56647m^3m^{-3}. Based on these results, the water content estimates is very high unlike mineral soil. Under natural conditions, the water content in peat exceeds 80% and gases content is about 6%. Hence, the water content in peat soil area is very high due to its soil properties itself. However the water content for peat soil is different at different areas. The appropriate of petrophysical relationship is needed to estimate the SWC from GPR data. Hence, we calculate the correlation of coefficient for each equation to illustrate the accuracy for both frequencies. Figure 4 illustrate the graph for comparison of water content from GPR common–offset measurements against dielectric permittivity for three petrophysical relationships. Based on the results, for 250MHz, estimates SWC from Roth's equation had R^2 of 0.9268 and R^2 for SWC from Schaap's equation is 0.9897. However, Idi’s equation had lower correlation of coefficient compared to other two equations. Roth’s equation has been developed using TDR for SWC estimation. The researchers reported that the error found for the equation is 0.035. Researcher [15] also applied the same method which used TDR with 505 measurements to develop site specific petrophysical relationship for SWC estimation. Unlike Roth and Schaap’s equation, Idi’s equation was developed using capacitance method for SWC estimation at peat soil area with 36 samples of measurements. The researchers used different approach for developing site specific petrophysical relationship at organic soil to estimate SWC. The number of measurements of the sampling is important for the equation to be formed. Hence, it will affect the outcome of the measurements for the future work.

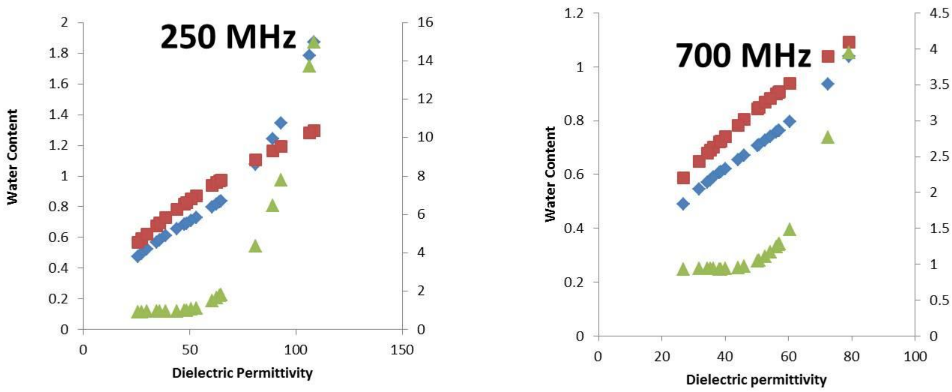

Figure 4. Comparison of water content from GPR common –offset measurements against dielectric permittivity for three petrophysical relationships

We have presented GPR Common-offset measurement to estimate SWC at peat soil area. To assess the accuracy of the GPR measurements along with using petrophysical relationships, the results were compared with volumetric water content from gravimetric measurements. Figure 5 shows comparison of GPR common-offset measurements with gravimetric measurements. The SWC of the peat soil from the common-offset measurements have been plotted together with gravimetric measurements data against depth. The variations of the 250MHz for Roth’s equation and Schaap’s equation agree with the gravimetric measurements. The GPR measurements estimates by Roth, Schaap and Idi’s equations followed the same trends as the gravimetric measurements but the absolute values of water content were significantly higher than those of gravimetric methods possibly due to the different sampling and depths associated with low frequency and conventional techniques. Besides, the development process for the site specific petrophysical relationship is also important as it will be applied for GPR and other’s method data. There are possible error during performing the measurements of developed the petrophysical relationship. Application of the petrophysical relationship using TDR – based relationship which used the TDR data with small scale measurements to GPR data also might be the source of error. There are also possible reason for the slightly differences for the difference between GPR measurements data and gravimetric measurements data could be inaccuracies in the density estimates used to convert gravimetric water content to volumetric water content. These inaccuracies could create error in the petrohysical relationship applied to the GPR data and gravimetric measurements data.

While previous studies have demonstrated the application of common-offset measurements for SWC estimates, they did not critically examine the SWC estimation at peat soil area. Our study has examined the use of common-offset measurements for SWC estimation at peat soil area. Further we applied dual frequencies for velocity determination to compute SWC at peat soil area. Even though the approach was conducted on a small scale area for SWC estimation using dual frequencies, we found that, to develop site specific petrophysical relationship, the number of measurements influence the outcome of the studies to provide better results and good measurements,. Besides, the method to estimate SWC for developed the equation also should be considered.

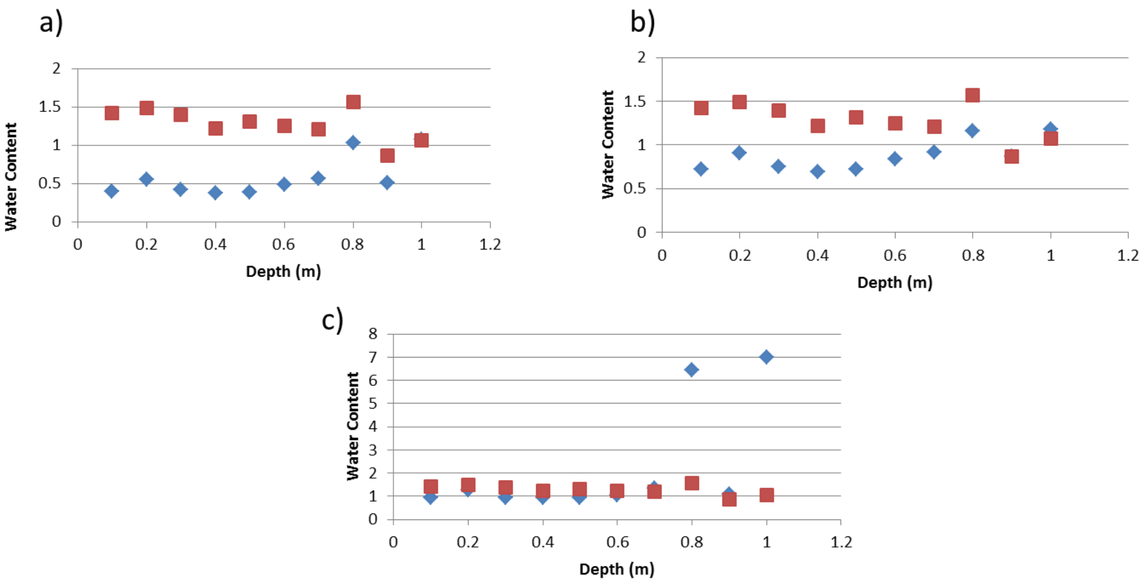

Figure 5. Comparison of GPR measurements and gravimetric measurements (A) Roth's equation; B) Schaap's equation; C) Idi's equation) on 250MHz

6. Conclusion

Ground penetrating radar is a geophysical tool that computes the volumetric water content using appropriate petrophysical relationship. We have examined the performance of the three petriphysical relationship to estimate SWC from GPR data. To assess the performance of the equations, the practical of common-offset measurements method was compared with gravimetric measurements. By comparing the results, Schaap's equation gives better results with correlation of 0.9897 compare to other equations. Besides, the Schaap's equation and Roth's equation follow the trend when comparing with gravimetric measurements. Unlike other equations, Idi's equation slightly over predicted the water content at the site. For the entire data that we analyzed using three petrophysical relationships, we found that Schaap's equation provided the best and most accurate results for water content. Shaap's equation gives the best results compare to other petrophysical relationships.

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