EnvironmentAsia
The international journal by the Thai Society of Higher Education Institutes on Environment

EnvironmentAsia 13(2) 2020 78-87
DOI 10.14456/ea.2020.31
ISSN 1906-1714; ONLINE ISSN: 2586-8861

Determination of the Volumetric Soil Water Content of Two Soil Types using Ground Penetrating Radar: A Case Study in Thailand

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Received: September 12, 2019; Revised: October 22, 2019; Accepted: January 18, 2020

Abstract

Determination of Volumetric Soil water content (VSWC) is important in many fields such as agriculture, hydrology, and ecology. At present, there are many methods to determine VSWC for example gravimetric, time-domain reflectometry (TDR), capacitance probe methods. In this study, ground penetrating radar (GPR) was used to determine VSWC of different soil types. One is a loam and another is loamy sand. The ground wave method with central frequency of 400 MHz antennas was used to acquire the GPR data. Then, the dielectric permittivities are converted to VSWC by Topp's equation. The results of water content calculated by gravimetric technique from soil samples at different depths (10, 20 and 30 cm) were used as the references. The results revealed that the VSWC of loam soil from GPR at depth 10 cm was correlated very well with the water content derived from gravimetric technique with the root mean square error (RMSE) value of 1.173 %. In loamy sand, the VSWC from GPR at depth to 20 cm was in good agreement with the VSWC from gravimetric technique with RMSE value of 5.978%. The comparisons of water content to gravimetric water content derived from both methods demonstrate that GPR can be used to offer fast, accurate, spatially dense, and non-invasive determination of VSWC in field-scale applications.

Keywords: Volumetric soil water content; Ground penetrating radar; Ground wave

1. Introduction

The volumetric soil water content (VSWC) in the vadose zone or unsaturated zone is significantly important in many fields such as soil science, hydrology and ecology, because it can provide data on the spatial distribution of soil water content at the near surface (Entekhabi *et al.*, 1996; Galagedara *et al.*, 2003; Galagedara *et al.*, 2005). Presently, there are several methods for determining the VSWC. These methods have different resolutions, measurements and observation scales.

At a small scale, gravimetric analysis technique is a point-measurement method. This method is very simple and precise. However, the disadvantage of this method is time-consuming and involves sample collection as well as point-measurements. Several sensors have been developed to be easy to use by pushing the sensor into the measurement point, such as time domain reflectrometry (TDR), neutron probes and capacitance probes. These tools are non-invasive but are point-measurements like the gravimetric method. The dielectric permittivity is a significant property of soil that can be converted to VSWC using the petrophysical relationship. The relationship between the relative dielectric permittivity and VSWC of various soil types was proposed by Topp *et al.* (1980), as shown in equation (1);

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

where θ is the VSWC and ε_r is the relative dielectric permittivity of the soil.

At a big scale, airborne and space borne remote sensing using electromagnetic waves (EMW), infrared and visible light bands have been developed. Their advantage is that a large scale can be covered within a short period of time. However, the data obtained from this method has a poor resolution and is easily contaminated by noise. An, alternative method to reduce those disadvantages is the use of ground penetrating radar (GPR). The GPR method is appropriate for field scale analysis and has an satisfactory accuracy for estimating the VSWC (Grote *et al*., 2003; Huisman *et al*., 2003; Galagedara *et al*., 2005; Weihermuller *et al*., 2007).

The GPR is one of geophysical methods that utilizes high-frequency EMW. GPR operates in various frequencies such as 100, 200, 400, or 900 MHz. The depth of penetration of GPR signal depends on its frequency and material properties. In general, higher frequency gives higher resolution of data but lower depth of penetration. Transmitter antenna (Tx) of the GPR send an EMW signal into the subsurface, where the different electrical properties of different media causes variations in the signal reflection or refraction to the receiver antenna (Rx) (Annan, 1973). The possible EMW travel paths in a two soil layers with different electrical properties are shown in Figure 1 (Sperl, 1999). Because water has a greater value of dielectric permittivity (about 81) than other geologic materials (average soil = 16, dry sand = 3 - 6) (Reynolds, 2011), it is a significant variable in changing the GPR signals. So, GPR is a potentially suitable technique for determining the VSWC (van Overmeeran *et al*., 1997).

To determine the VSWC of soil, the variables such as the travel time and velocity are calculated to find the relative dielectric permittivity of the soil, and then both variables are converted to the VSWC by using equation (1). There are many configurations for GPR technique each with different advantages and disadvantages. Four techniques to use GPR for determining the VSWC of soil have been reviewed by Huisman *et al*., 2003 and include (i) reflected wave, (ii) ground wave, (iii) transmitted wave and (iv) surface reflection coefficient, but selecting the suitable technique depends on the objective(s) of the study.

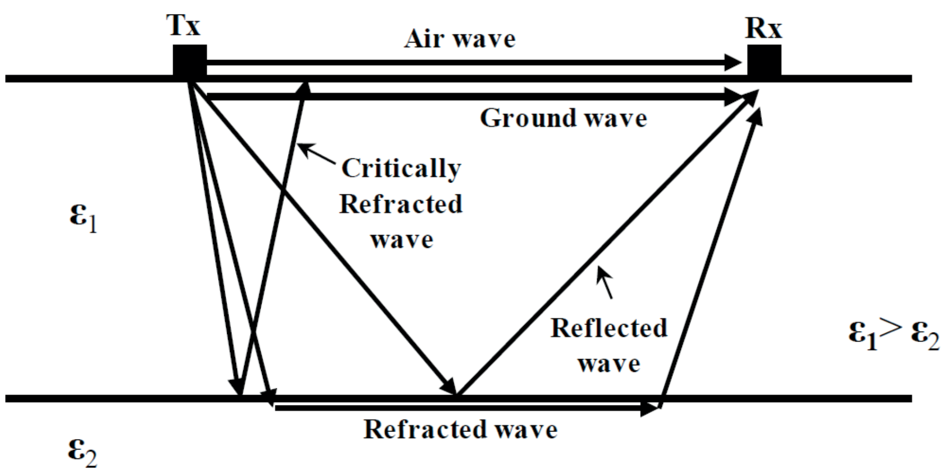


Figure 1. Schematic illustration of the propagation paths of EMWs in two different soil layers with different dielectric permittivities (Sperl, 1999).

This study used the ground wave technique, which uses the travel time of the ground wave to easily calculate the dielectric permittivity of soils. For a fixed offset configuration, Tx and Rx are fixed at a constant separation along the surveying line, which is easy and fast to perform (Huisman *et al*., 2003). The benefit of ground wave technique over other techniques is that the ground wave can easily be recognized on data and data acquisition can be performed in a continuous manner. Moreover, the GPR data can be acquired very fast and covered a large area in a short period of time.

To find the dielectric permittivity, the travel time of air and ground waves are used as the input parameters in the equation of the EMW velocity and dielectric permittivity (Weihermuller *et al*., 2007), as shown in equation (2);

$$\varepsilon_{Soil} = \left(\frac{c}{v}\right)^2 = \left(\frac{c(t_{GW} - t_{AW}) + x}{x}\right)^2 \quad (2)$$

where ε_{Soil} is the relative dielectric permittivity of soil, *c* is speed of light in free space (299,792,458 m/s), t_{GW} is the ground wave travel time, t_{AW} is the air wave travel time and *x* is the travel distance (equal to antenna separation). The dielectric permittivity is then converted to the VSWC by equation (1).

The major disadvantage of the ground wave technique is the difficulty in clearly separating the ground and air waves in the data. At short an antenna separation, their signals may be close and so this will cause interference making it hard to identify, especially in dry soil (Grote *et al*., 2003; Grote *et al*., 2010). On the other hand, at large an antenna separation, the effect of interference from air waves may occur. Thus, an appropriate antenna separation is significant for this technique.

In this study, the ground wave technique was used with a central frequency of 400 MHz. The aim was to determine the VSWC with GPR in direct comparison to gravimetric method of two different soil types. In addition, the appropriate data acquisition, processing and interpretation methods were discussed, and the capability of GPR for determining the VSWC compared with the direct gravimetric method was evaluated.

2. Materials and Methods

2.1 Study Areas

Two study areas are used in this study, each being 10 m wide, 20 m long and aligned north-south direction at 43 m above mean sea level. The reason for selecting these two sites are that both sites have different soil types and agricultural activities. For each site, there are 11 GPR lines and nine soil sampling points (Figure 2), each sampled at 10, 20 and 30 cm depth, giving a total of 27 soil samples per site for the gravimetric analysis. The first study site is in the center of the Chulalongkorn University campus in Saraburi province, central Thailand (Figure 3a) (Thitimakorn *et al*., 2016). The starting point is at the south-west corner of the site at 14º 31´ 14.5´´ N and 101º 2´ 7.1´´ E. The experimental field is a foot hill plain with the hill situated to the east of the site. The rocks in the area are volcanic rocks, such as rhyolite, andesite and volcanic breccia. The soil texture is a loam soil (Table 1) with an average soil density of ~1.43 $g.cm^{-3}$. The area has a tropical savanna climate with an average annual temperature of 28ºC, and the maximum rainfall is in May to October. The major land use is for agriculture, such as grass or corn.

The second study area is in the Huay Sai Royal Development Study Center, Petchaburi, western Thailand, with the starting point at 12º 42´ 14.9´´ N and 99º 54´ 28.0´´ E (Figure 3b). This site is at south west about 235 kilometres far from Saraburi site, as shown in figure 4. The geography of the experimental field is a foot hill plain with the hill situated to the north-west. The soils in the area are weathering sedimentary rocks, such as gravel, sand, silt and laterite, and the soil texture was loamy sand (Table 1) with an average density of ~1.68 g/cm. The climate is hot and dry and is affected by the southwest and northeast monsoons with an average annual temperature of 28.4 ºC and maximum rainfall in October to November. The principal land use is agriculture, such as sugar cane and pine apple.

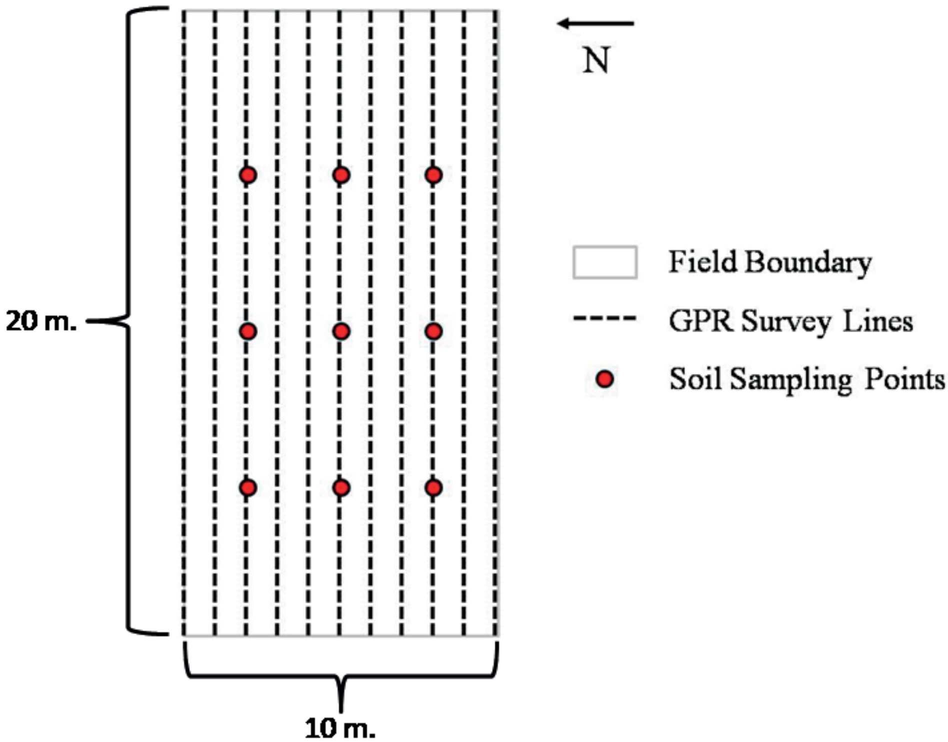


Figure 2. Schematic diagram of the GPR survey lines and soil sampling points in both study sites.

Table 1. Soil texture of the two study areas at a depth of 10, 20 and 30 cm from the surface.

Study area	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture
Saraburi Province	10	49.00	34.80	16.20	Loam
	20	42.00	38.80	19.20	Loam
	30	40.00	39.80	20.20	Clay Loam
Petchaburi Province	10	81.00	14.60	4.40	Loamy Sand
	20	83.00	11.60	5.40	Loamy Sand
	30	85.00	10.60	4.40	Loamy Sand

a) **b)**

Figure 3. View of the two experimental sites with the GPR survey lines marked on the ground. (a) Loamy (to clay loam at 30 cm) soil site at Saraburi province and (b) loamy sand soil site at Petchaburi province.

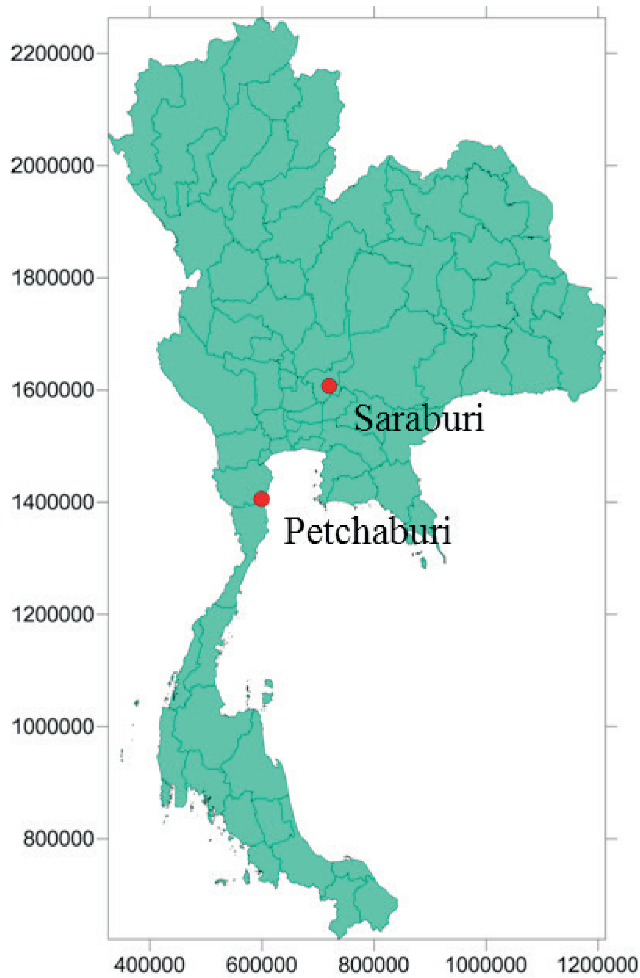


Figure 4. Location of study areas at Saraburi and Petchaburi Provinces.

2.2 Samplings

In this study, the GSSI system was used to acquire the GPR data with ground coupled mono static antenna. The mono static antenna contains both the Tx and Rx within the same housing. This housing can effectively protect them from environmental noise. A frequency of 400 MHz was used, and the antenna was laid on a sledge with a towline in front of the sledge and odometer on the back (Figure 5). In this study, two GPR boxes were used because the required separation distance of the antenna for the ground wave fixed offset technique. One box was used as a transmitter and another one was used as a receiver. The antenna separation was 1 m as recommended by many studies (Huisman *et al*., 2002; Grote *et al*., 2003; Grote *et al*., 2010). The GPR data were collected and processed using the SIR 20 and RADAN 6.6 software, respectively. The survey at Saraburi site was performed on 29th July 2014 in the early rainy season. The second site at Petchaburi was acquired on 3rd August 2014. The ground condition of both sites was semi dry during data acquisition.

Soil samples were collected at nine sampling points per field site (Figure 2) using an auger immediately after the GPR surveying. The samples, collected at depths of 0 – 10 cm, 10 – 20 cm and 20 - 30 cm from the surface, were analyzed for gravimetric water content by technique recommended by ASTM standard (ASTM D2216 – 19).

3. Results and Discussions

3.1 GPR Data Processing for Calculating the VSWC

For acquiring the VSWC data, the Tx and Rx antenna was set on the sledge with the fixed offset distance and towed with walking speed (approximately 1.5 ms^{-1}) along eleven survey lines. The results are presented in Figure 6a. By using equation. (2), the input data is the different travel time at each distance that could be identified from the highest amplitude of the signal of interest (selected by the researcher) using the EZ Tracker command in RADAN 6.6 software, shown as the dotted lines in Figure 6b. Each survey line had many GPR sampling points because there were 100 scans of EMW pulses per meter. So, VSWC estimated by GPR can be calculated from many points of data. Every 10 cm, the EZ tracker software was set to track the GPR signal. So, in this study, there were potentially 2,200 VSWC points of determination.

3.2 Analysis

At Saraburi site with loam soil, the VSWC from gravimetric method was 28.869 – 32.981 (mean = 30.297), 25.283 – 35.070 (mean = 29.627) and 3.682 – 34.459 (mean = 30.098) at 10, 20 and 30 cm depth, respectively. The VSWC derived from GPR method was 18.161 – 39.727 (mean = 30.977) (Table 2).

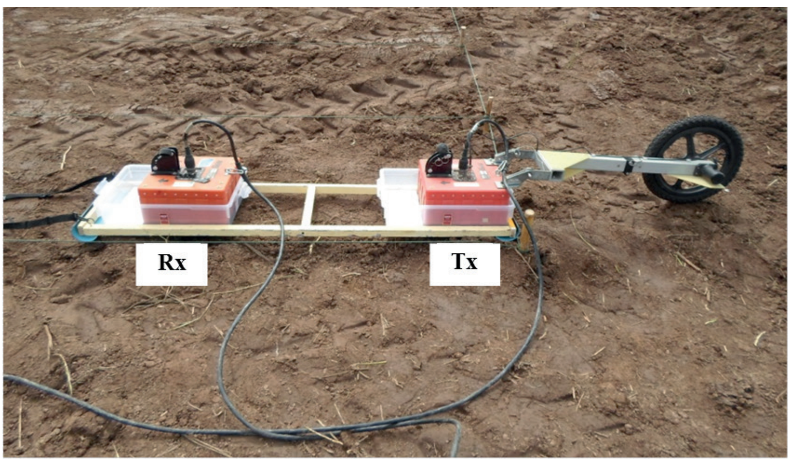
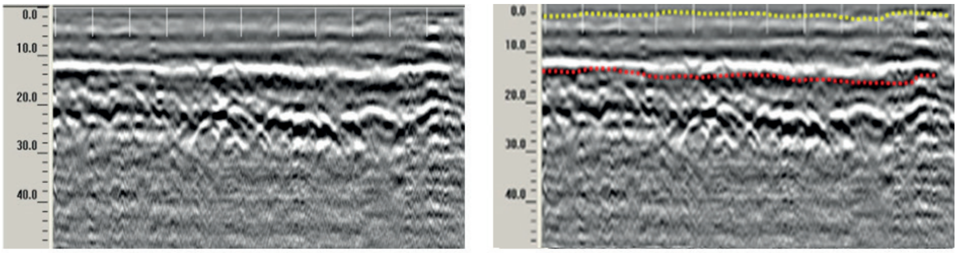


Figure 5. GPR system with 400 MHz central frequency on a sledge. A 1 m antenna separation (Rx to Tx) was used in both sites.

The VSWC contour map derived from GPR (Figure 7 left) showed the highest VSWC in the northwestern part of the site that gradually decreased towards the southeastern part.

For Petchaburi site with loamy sand soil, the VSWC was much lower than Saraburi site because the low of rainfall level (Table 3). The gravimetric method gave a VSWC about 0.732–20.253 (mean = 5.862), 0.862 – 14.445 (mean = 4.450) and 1.190 – 10.898 (mean = 3.181) at a depth of 10, 20 and 30 cm, respectively. Whereas the VSWC derived from GPR was 0.354 – 26.820 (mean = 7.867). The VSWC contour map (Figure 7 right) showed the mostly dry area with a high VSWC at some points.



a) **b)**

Figure 6. Example of the GPR signals of line no. 7 which was processed by EZ Tracker, (a) before and (b) after tracking. The yellow dot represents air wave and the red dot represents ground wave.

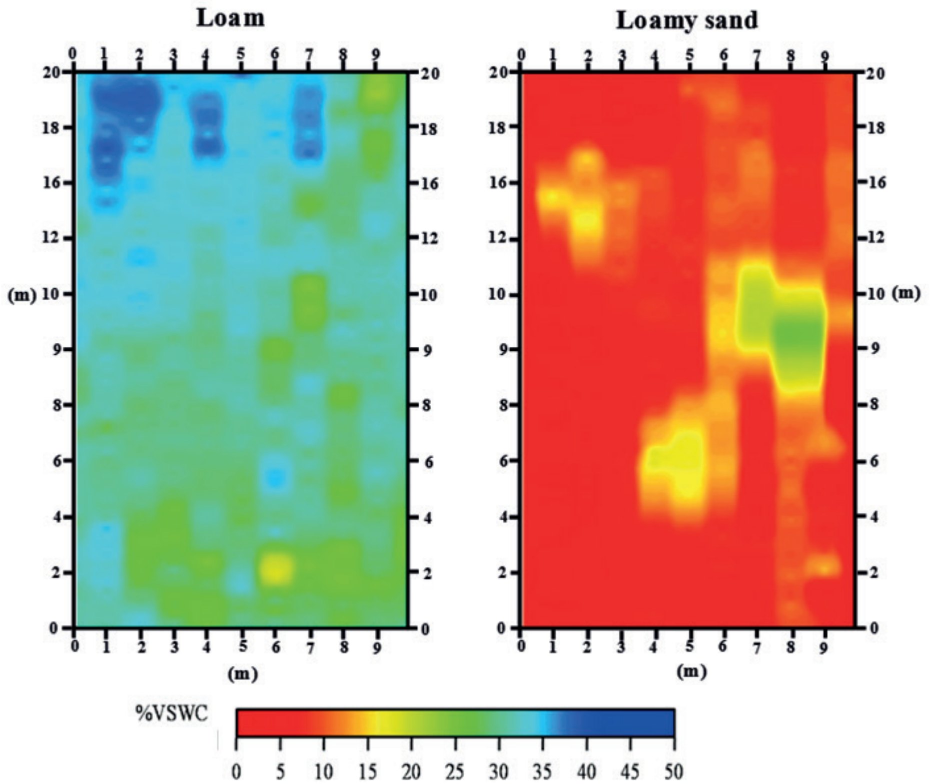


Figure 7. GPR-derived VSWC map for the (Left) loam and (Right) loamy sand soil types. The loam soil generally showed a VSWC of 20–35% but a high VSWC was observed in the upper part. The loamy sand showed a very low VSWC in most of the area but there were some high VSWC spots in the central part.

Table 2. VSWC (% cm3.cm-3) from gravimetric and GPR of total 9 soil samples at each depth of the Saraburi site. Note that the data of GPR were picked at the nearest points of soil samples. But the average of GPR was calculated from all GPR data.

Soil Sample	Gravimetric			GPR
	10 cm	20 cm	30 cm	
1	28.88	28.32	28.05	29.98
2	29.47	31.22	34.46	29.29
3	32.40	35.07	27.49	32.03
4	29.58	27.03	30.28	29.63
5	30.46	25.28	31.30	31.69
6	32.98	32.05	30.30	31.69
7	28.87	29.00	33.72	26.11
8	30.06	31.27	31.60	30.32
9	29.98	27.42	23.68	30.32
Average	30.30	29.63	30.10	30.98

Table 3. VSWC (% cm3.cm-3) from gravimetric and GPR of total 9 soil samples at each depth of the Petchaburi site. Note that the data of GPR were picked at the nearest points of soil samples. But the average of GPR was calculated from all GPR data.

Soil Sample	Gravimetric			GPR
	10 cm	20 cm	30 cm	
1	0.81	1.59	2.10	3.78
2	1.02	0.86	1.51	3.51
3	13.87	9.09	N/A	15.31
4	12.19	7.50	2.17	16.37
5	0.85	1.06	1.23	6.67
6	1.65	1.58	N/A	7.60
7	0.73	1.55	1.19	11.50
8	20.25	14.45	10.90	23.59
9	1.38	2.38	N/A	7.91
Average	5.86	4.45	3.18	7.87

GPR propagated EMW to pass through the whole soil. So, the comparison between the VSWC from GPR and gravimetric method at each site should use average value from surface to specific depth, rather than the value at a specific depth. In addition, the approximate penetration depth (influent depth) of the GPR is about half of wavelength (Du and Rummel, 1994; Du, 1996). For a loam soil at Saraburi site, the average VSWC from gravimetric and GPR showed a nonlinear relationship at all three depths. But only at depth of 10 cm, the correlation is good (0.732) (Figure 8), which corresponds to the GPR influent depth of 8 cm. For a loamy sand soil at Petchaburi site, the average VSWC from gravimetric and GPR showed a linear relationship with a good correlation at all three depths (Figure 8). The best correlation is at 20 cm (0.933), which accords to the influent depth of 21 cm.

The root mean square error (RMSE) of the Petchaburi site (5.978%) was much higher than that of the Saraburi site (1.173%) which may suggest that the VSWC derived from Topp's equation was overestimated to dry soil more than wet soil. The site-specific petrophysical relations may need to be established in order to accurately estimate the VSWC for a particular site. However, this was not performed at both sites in this study because of the limited number of sampled.

The loam soil (Saraburi) showed a lower correlation between the VSWC from gravimetric and GPR than the loamy sand (Petchaburi) because of the ground wave attenuation. Soil composed of a high level of silt and clay is not very amenable to GPR surveys because the electric conductivity from the water in the silt and clay has a strong ability to attenuate the EMW

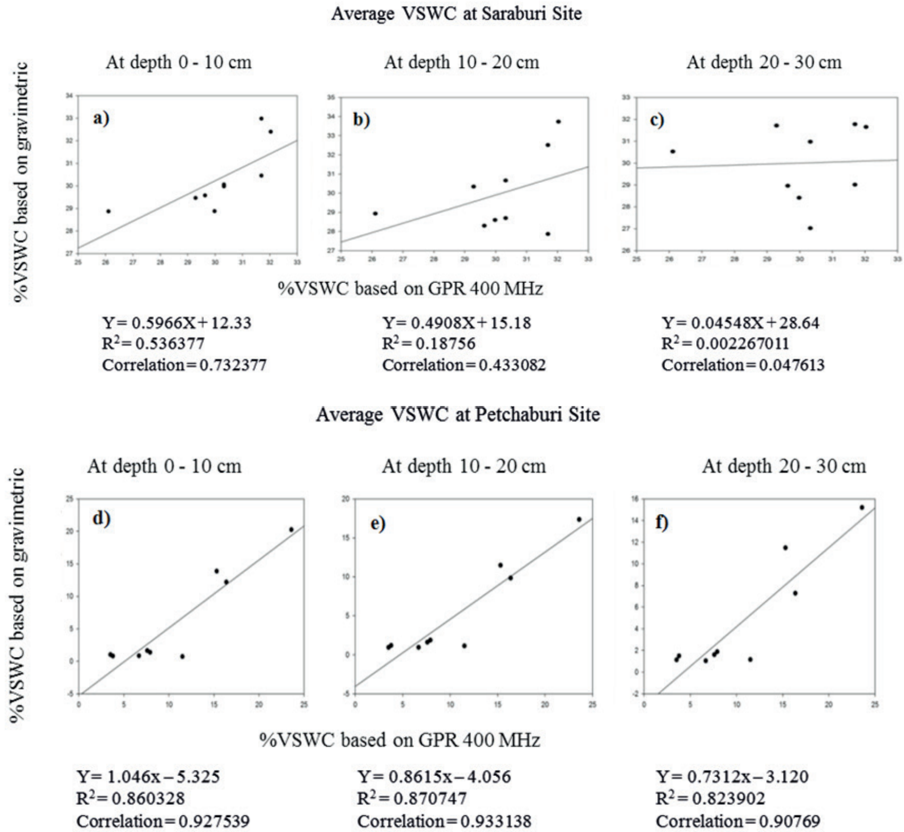


Figure 8. Relationship between the gravimetric- and GPR-derived VSWC values for the (a–c) loamy soil at Saraburi and (d–f) loamy sandy soil at Petchaburi at a soil depth of (a, d) 10 cm, (b, e) 20 cm and (c, f) 30 cm.

(Huisman *et al*., 2001). So, GPR is good for sandy soil. However, that the loamy sand had a higher RMSE than the loam maybe because of the drought at the time of this study that made the ground waves closer to airwaves and increased the error level.

4. Conclusions

The ability of GPR to determine the VSWC was evaluated by comparison with the gravimetric method in two different soil types. The first site was a loam soil with high clay content, while the second site was a loamy sand soil with lower clay content than the first site. Acquisition of the GPR data with 400 MHz antenna was optimal with a fixed offset of 1 m between the Tx and Rx antenna. With this GPR setting, the VSWC estimated by GPR were in good agreement with the gravimetric method at a depth of 10 cm (RMSE of 1.173%) for the loam soil at Saraburi and 20 cm (RMSE of 5.978%) for the loamy sand soil at Petchaburi. The influent depth of GPR at the Petchaburi site (20 cm) was a little bit deeper that at the Saraburi site (8 cm), which is probably due to the higher clay content of the Saraburi site. Overall, the GPR technique offers a fast, accurate and non-invasive determination of the VSWC in field-scale applications.

Acknowledgments

This study was sponsored by the Ratchadaphiseksomphot Endowment Fund Chulalongkorn University (R/F_2557_012_04_23) and THE 90^{th} ANINIVERSARY OF CHULALONGORN UNIVERSITY FUND (Ratchadaphiseksomphot Endowment Fund) We also thank Geology department, Faculty of Science, Chulalongkorn University for supporting field equipments. We also thank the STS Engineering Consultants Co., Ltd. for providing the GPR antenna used in this study.

References

Annan AP. Radio interferometry depth sounding: part I-theoretical discussion. Geophysics 1973; 38(3): 557-580.

Du S, Rummel P. Reconnaissance studies of moisture in the subsurface with GPR. In Proceedings of the Fifth International Conference on Ground Penetrating Radar, Waterloo Center for Groundwater Research, Waterloo, Ontario, Canada 1994: 1241–1248.

Du S. Determination of water content in the subsurface with the ground wave of ground penetrating radar. [Ph.D. Thesis.] 1996, Ludwig-Maximilians-Universitat, München.

Entekhabi D, Rodriguez-Iturbe I, Castelli F. Mutual interaction of soil moisture state and atmospheric processes. Journal of hydrology 1996; 184:3-17.

Galagedara LW, Parkin GW, Redman JD. An analysis of the ground-penetrating radar direct ground wave method for soil water content measurement. Hydrological processes 2003; 17: 3615-3628.

Galagedara LW, Parkin GW, Redman JD, Bertoldi PV, Endres AL. Field studies of the GPR ground wave method for estimating soil water content during irrigation and drainage. Journal of hydrology 2005; 301: 182-197.

Grote K, Hubbard S, Rubin Y. Field-scale estimation of volumetric water content using ground-penetrating radar ground wave techniques. Water resources research 2003; 39(11): doi:10.1029/2003WR002045.

Grote K, Anger C, Kelly B, Hubbard S, Rubin Y. Characterization of soil water content variability and soil texture using GPR groundwave techniques. Journal of Environmental and Engineering Geophysics 2010; 15: 93-110.

Huisman JA, Sperl C, Bouten W, Verstraten JM. Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar. Journal of Hydrology 2001; 245: 48–58.

Huisman JA, Snepvangers JJJC, Bouten W, Heuvelink GBM. Mapping spatial variation in surface soil water content: comparison of ground-penetrating radar and time domain reflectometry. Journal of hydrology 2002; 269: 194-207.

Huisman JA, Hubbard SS, Redman JD, Annan AP. Measuring soil water content with ground penetrating radar: a review. Vadose zone journal 2003; 2: 476-491.

Reynolds JM. An Introduction to Applied and Environmental Geophysics, Wiley; 2011.

Sperl C. Erfassung der raum-zeitlichen Variation des Bodenwassergehaltes in einem Agrarökosystem mit dem Ground Penetrating Radar. [Ph.D. Thesis.] 1999; Technische Universität München.

Thitimakorn T, Kummode S, Kupongsak S. Determination of Spatial and Temporal Variations of Volumetric Soil Water Content Using Ground Penetrating Radar: A Case Study in Thailand, Applied Environmental Research 2016; 38(2): 33-46.

Topp GC, Davis JL, Annan AP. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resources Research 1080; 16:574–582.

Van Overmeeren RA, Sariowan SV, Gehrels JC. Ground penetrating radar for determining volumetric soil water content; Results of comparative measurements at two test sites. Journal of Hydrology 1997; 197: 316–338.

Weihermuller L, Huisman JA, Lambot S, Herbst M, Vereechken H. Mapping the spatial variation of soil water content at the field scale with different ground penetrating radar techniques. Journal of hydrology 2007; 340: 205-216.