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Determination of Spatial and Temporal Variations of Volumetric Soil Water Content Using Ground Penetrating Radar: A Case Study in Thailand

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Abstract

In this research, ground penetrating radar (GPR) was used to determine the volumetric soil water content (VSWC) of a loamy soil. The GPR was set up in the ground wave fixed offset method using both 400 and 900 MHz frequency antennae. By estimating the relative dielectric permittivity of the soils, these values were converted to the VSWC by Topp's equation. The gravimetrically calculated VSWC values from the soil samples at different depths were used as the references. In addition, the ability of the GPR method to detect variation in the VSWC over time was evaluated in three periods spanning the dry and rainy seasons. The VSWC estimated from the 400 MHz analysis had a high correlation with the gravimetric method under dry conditions at a soil depth of 10–30 cm and under wet conditions, the result was reasonable at 10–20 cm. In contrast, the 900 MHz derived VSWC estimates were not related to those from the gravimetric analysis, although the results were reasonable in dry conditions. The VSWC values obtained from the 400 MHz antenna give a reasonable estimation of VSWC of this site. Thus, the GPR method is appropriate for estimating the VSWC due to the ease of data acquisition and processing.

Keywords: Soil Water Content; GPR; Ground Wave

Introduction

Knowledge about the soil water content in the root zone (also known as the vadose or unsaturated zone) is important in many fields, including soil science, hydrology and ecology, because it provides data on the spatial distribution of water at the land surface. There are many methods for determining soil water content at different resolutions and scales of measurement.

At a small scale, gravimetric determination is a conventional point-measurement method based upon the weight difference between fresh (wet weight) and dried soil, and so requires collecting soil samples and baking them at 105–110 °C for 24 h (or until at constant weight). Though simple and accurate, this method is tedious, time-consuming, requires invasive sampling and point-measurements. By using the principles of physics, many types of sensors have been developed that are easy to use by inserting probes into the soil at the measurement point; such probes include neutron probes, time domain reflectrometry and capacitance probes. The dielectric constant is an important property of the soil that can be converted to volumetric soil water content (VSWC) using the petrophysical relationship. The relationship between the relative dielectric permittivity of various mineral soil textures and the VSWC has been proposed [9], with the most common expression being Eq. 1;

These sensors are easy to handle and non-invasive but are still point-measurements like the gravimetric approach. At a large scale, both air- and space-borne remote sensing using electromagnetic s (EMW) in the radio wave, infrared and visible light bands have been used. These have the advantage of offering the ability to perform a large scale survey in a short time; however, they have low data resolution and are easily disturbed. An alternative method to reduce those disadvantages is the use of ground penetrating radar (GPR), which is suitable for small to field scales, and typically has an acceptable accuracy for estimating the VSWC [6].

As stated, GPR is a geophysical method that uses high-frequency EMW. The transmitting antenna (Tx) of GPR sends an EMW signal into the ground and the signal is reflected or refracted back to the receiving antenna (Rx) for analysis (Figure 1) depending on the different soil properties. An important property of the medium is its dielectric permittivity, and this is especially the case for water, which has a much larger value than other geologic materials. Thus, water content is a significant determinant of the total GPR signal, making GPR a potentially appropriate technique for measuring the VSWC. There are many configurations of GPR surveying that differ in their accuracy and resolution, depending on signal frequency, ray paths and soil conditions [8]. Indeed, as with conventional survey methods, a suitable surveying technique and data processing is required for accuracy in estimating the VSWC to provide high quality data.

$$\theta = 4.3 \times 10^{-6} \varepsilon_r^3 - 5.5 \times 10^{-4} \varepsilon_r^2 + 2.92 \times 10^{-2} \varepsilon_r - 5.3 \times 10^{-2}, \qquad \text{(Eq.1)}$$

Where θ is the VSWC (m^3/m^3) and ε_r is the relative dielectric permittivity of the soil

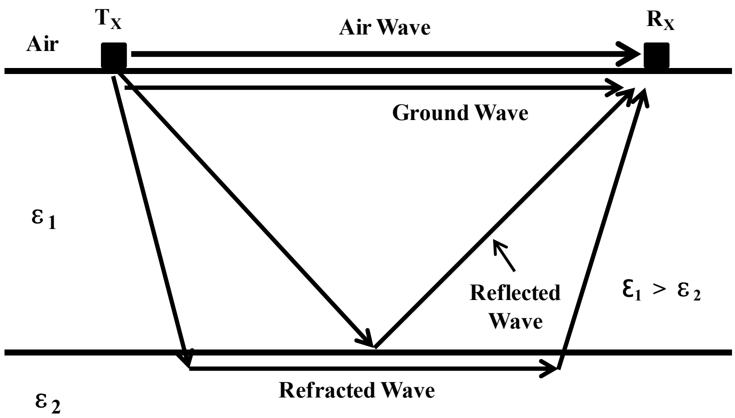


Figure 1 Propagation paths of radar waves in a soil with two layers of contrasting dielectric permittivity (ε_1 and ε_2)

To estimate the VSWC by GPR, variables including time travelled, speed and amplitude, are calculated to find the relative dielectric permittivity of the soil; this value is then converted to the VSWC using Topp's equation. There are many surveying configurations offering different advantages and conditions [6]. For example, for the GPR frequency (such as 100, 450 or 900 MHz), a higher frequency gives a higher resolution of data but a lower depth of penetration [6]. The EMW from the Tx propagates into the soil in all directions, so waves arriving to the Rx come from different ray paths, such as the air wave, ground wave and reflected or refracted waves from the contrast in the dielectric constants of different soil media.

Thus, the configuration of the equipment affects surveying speed and results, such as on-ground surveying [4, 7], off-ground surveying [1, 10], or borehole surveying [11]. The four GPR methods used to estimate the VSWC are the (i) reflected wave, (ii) ground wave, (iii) transmitted wave and (iv) surface reflection coefficient; these have been reviewed elsewhere [6]. Choosing the appropriate method depends on the survey objectives.

This research used the ground wave technique, which uses the time travel of ground waves to calculate the dielectric constant. A fixed offset configuration, where the Tx and Rx antenna are fixed at a constant separation distance, was used along the survey line as it is easy and fast. To find the dielectric constant, the air and ground waves are assumed to travel in a straight line be-tween antennae, and are used as the input in Eq. 2 for determining the EMW velocity and dielectric constant [10];

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

The ε_{Soil} is the relative dielectric permittivity of soil, c is the speed of light in free space (299,792,458 m/s), t_{GW} is the ground wave travel time (s), t_{AW} is the air wave travel time (s) and x is the wave travel distance (m) (equal to the antenna separation). The obtained dielectric constant was then converted to the VSWC by Topp's equation [3, 5, 6, 10, 11].

An important disadvantage in using the ground wave is the difficulty in observing the separation of the ground and air waves from each other. At too short an antenna separation, their signals may overlap so that interference occurs which is hard to identify, especially in dry soil [4]. At too large an antenna separation, a ringing effect of the air wave may occur. Thus, proper antenna separation is important for this technique. This is achieved by surveying with wide angle reflection and refraction (WARR), a multi-offset reflected wave method. In this study, the Tx antenna was fixed at the midpoint of the study area and the Rx antenna was moved away with every signal transmitted by 2 cm over a total distance of 4 m for 400 MHz antenna. On the other hand, for 900 MHz, the Rx antenna was moved away with 1 cm each signal transmitting over the total distance of 2 m. From the WARR results, the suitable antenna separation distance was selected and a sledge-like instrument was built to carry the antenna in the fixed offset survey. In addition, the WARR analysis can estimate the influent depth of the GPR, about half of the EMW wavelength, by calculating the ground wave velocity [2].

Using GPR with a ground wave fixed-offset technique and antenna of a central frequency of 400 and 900 MHz, the primary objectives of this study were to estimate the VSWC with GPR in comparison to the gravimetric method, and to determine the effectiveness of the GPR technique in monitoring variations in the VSWC over time with different rainfall levels. In addition, the appropriate data acquisition, processing and interpretation methods were studied, and the accuracy of GPR for determining the VSWC compared with the direct gravimetric method was evaluated. Although similar research has been performed in many other countries around the world [1, 4, 5, 7, 10], this has never been reported in Thailand before.

Study Area

The study area is located in the Center of Learning Network for the Region (CLNR), Chulalongkorn University, Saraburi province, central Thailand (Figure 2). The experimental field (10 m wide by 20 m long in a north-south alignment) is a foothill plain with a hill at the east. The rocks in the area are volcanic rocks, such as rhyolite, andesite and volcanic breccias. A total of 11 lines were used for the GPR analyses and nine soil sampling points, each at 10, 20 and 30 cm depth (total of 27 soil samples), were used for the gravimetric analysis (Figure 3). The starting point was at the south-west corner of the field at latitude 14º 31´ 14.5´´ N and longitude 101º 2´ 7.1´´ E, at an altitude of 43 m above mean sea level.

Some soil samples were sent to the Agricultural Production Science Research and Development Division, Department of Agriculture for soil texture classification by using the hydrometer method. Table 1 presents the percentage of sand, silt and clay in the soil at a depth of 10, 20 and 30 cm. Using the United States Department of Agriculture (USDA) standard, the soil texture at all three depths was classified as a loamy soil. The average soil density was 1.43 g/cm^3. Climate of the site is Tropical Savanna with an average temperature of 29ºC and maximum rainfall from May to October. Land use was predominantly agricultural, such as grass or corn.

To evaluate variation in the VSWC with time at different rainfall levels, three data acquisitions were conducted at different times of the year in order to compare the derived water contents. The first survey was performed on 29th July 2014 in the early rainy season, the second on 23rd November 2014 at the end of the rainy season, and the third on 10th February 2015 in the dry season (winter). On each of the three sampling days there was no rainfall, but the total rainfall accumulation in the one month period prior to each sampling day was 107.4 mm, 94.6 mm and 0 mm, respectively, as measured at weather station S.9 (5445) at Kaeng Khoi District, Saraburi province (11.93 km due north from the study site).

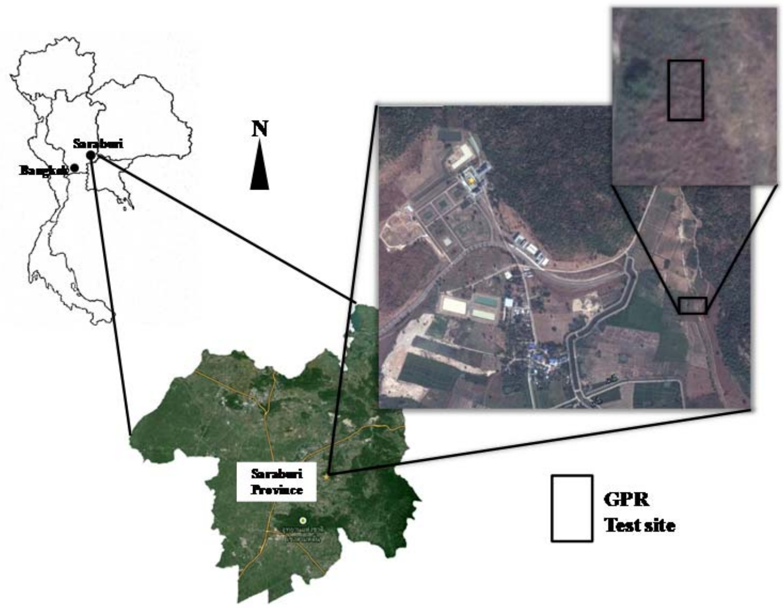


Figure 2 Location map of the GPR test site at the CLNR, Chulalongkorn University, Saraburi province, central Thailand (not to scale)

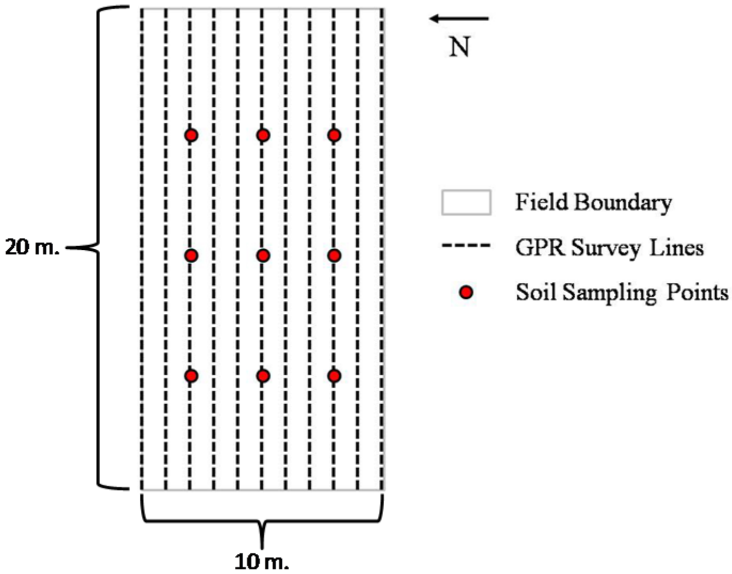


Figure 3 Schematic diagram of the GPR survey lines and soil sampling points

Table 1 Soil texture at the study area at depths of 10, 20 and 30 cm

Depth (cm)	Sand (%)[a)]	Silt (%)[a)]	Clay (%)[a)]	Texture
10	49.00	34.80	16.20	Loam
20	42.00	38.80	19.20	Loam
30	40.00	39.80	20.20	Loam

[a)]Data are shown as the mean of 9 soil samples per depth

Materials and methods

1) GPR system

This research used the GSSI system with ground coupled antenna models. This system contains both the Tx and Rx within the same box; the housing or shield effectively protects them from environmental noise. A central frequency of 400 or 900 MHz was used. The equipment was laid on a sledge, constructed by connecting two plastic boxes with wooden rods, as shown in Figure 4. The front of the sledge has a tow-line for moving the equipment to new sites; the rear has a distance-calibrated survey-wheel and each of the two GSSI antenna boxes is mounted in a plastic box with the curved PVC used as a bumper for protection. Two boxes were used because the required antenna separation distance for the ground wave fixed offset technique was greater than the GPR housing, so the front box was set to be the Rx antenna only and the rear box as the Tx antenna only. The plastic boxes were firmly attached to the ground in use to reduce the effect of air and to stabilize the signal. The software used for data collection was SIR 20 and the processing software was RADAN 6.6.

2) Gravimetric based estimation of VSWC

The results of the GPR data were compared with the estimated VSWC from the gravimetric analysis of nine sampling points at three depths (Figure 3) as the standard, taken from the same 27 soil samples. Soil samples were collected by hand auger immediately after GPR surveying and then sealed in bags to transport to the laboratory for subsequent gravimetric determination of the water content. For the latter, the soil samples were weighed then baked in an oven at 105 ºC for 24 h, cooled to room temperature and reweighed. The difference in weight was ascribed to the mass of water.

Figure 4 Sledge setup for the 400 MHz GPR (Left) and 900 MHz GPR (Right) survey systems

Results

1) WARR analysis

The correct Tx and Rx antenna separation distance is the key factor in ground wave fixed-offset surveying in order to obtain an accurate discrimination between the air and ground waves. The result of the WARR analysis at the study site is shown in Figure 5, where the red rectangular box shows the antenna separation distance at which the ground wave was clearly separated from the air wave. In this study, the optimal separation between the Tx and Rx GPR boxes on the sledge was 100 and 40.5 cm for 400 MHz GPR and 900 MHz respectively.

In addition, the results from the WARR analysis were used to calculate the ground wave velocity and used to find the influent depth from Eq. 2. The approximate ground wave velocity of both the 400 and 900 MHz frequency was 6.45×10^7 m/s, giving an influent depth of 8 and 4 cm for the 400 MHz and 900 MHz, respectively. Note, however, the WARR analysis was only performed on the first survey date (early rainy season, 29th July 2014) and these values were also used on the two subsequent sampling dates (late rainy season and winter dry season on 23rd November 2014 and 10th February 2015, respectively).

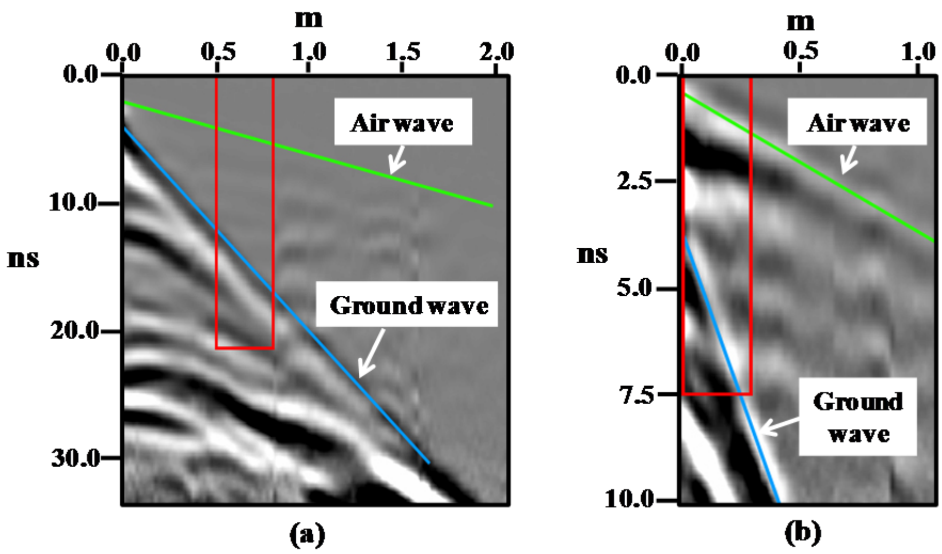


Figure 5 The results from the WARR analysis of the (a) 400 MHz GPR and (b) 900 MHz GPR of the study site on 29th July 2014 (early rainy season). The red box shows the optimal Tx and Rx antenna separation distance for clear resolution of the ground and air waves.

2) Data processing for calculating the VSWC

The fixed offset Tx and Rx antenna on the sledge was towed along eleven survey lines at walking speed (approximately 1.5 m/s). Representative results from the 400 MHz GPR are shown in Figure 6 (a). The different travel time at each distance is required as an input to Eq. 2. By using the EZ Tracker command in RADAN 6.6, the highest amplitude of the signal of interest (i.e. picked by the researcher) is identified, as shown with dotted lines in Figure 6 (b). Because the EMW pulses of GPR are sent at about 100 scan/ m, each survey line has many GPR sampling points. So, estimating the VSWC by GPR involves many points that can be acquired faster than conventional point-measurement methods. The EZ Tracker was set up to track the signal every 10 cm, so there were about 2,200 VSWC data points per survey.

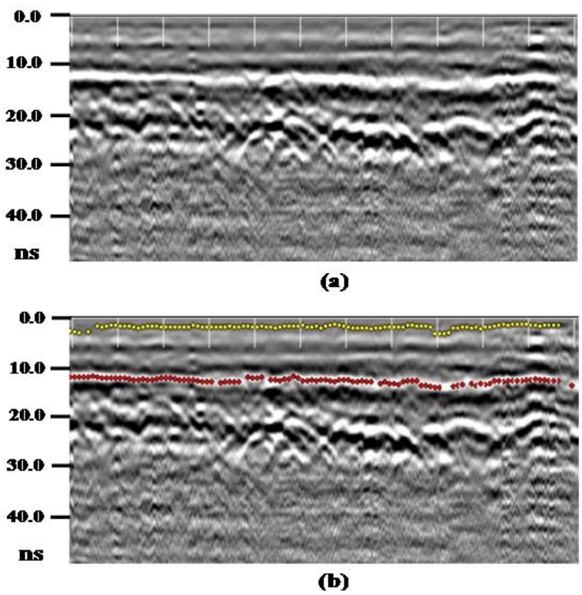


Figure 6 Example of the signal from the 400 MHz GPR processed by the EZ Tracker command (a) before and (b) after tracking

3) Estimation of the VSWC

The results of the VSWC estimation at each soil depth are shown in terms of the %VSWC in Table 2. The first survey was performed in the early part of the rainy season (29th July 2014). The gravimetric method did not show any tendency of the VSWC to vary with the soil depth in any clear pattern. The VSWC estimates derived from the GPR 400 MHz and GPR 900 MHz are illustrated as a color contour map in Figure 7. This interpolated VSWC contour map was obtained by the krigging technique with a 10 cm grid. The VSWC estimates ranged from about 0% to 50%. For the GPR 400 MHz analysis, the VSWC was high in the north to north-west part of the survey field (36–42%) and gradually decreased to the south-east (26–28%). However, the GPR 900 MHz derived result was rather different. Firstly, the VSWC values obtained were about half of those from the GPR 400 MHz survey. Secondly, the pattern was quite different, with the appearance of a larger dry area at the center of the field (< 16%) in a north-south orientation.

The second survey was performed at the end of rainy season (23rd November 2014), when it was expected that there would be a higher VSWC than in the first survey period. The gravimetric analysis showed only a very small increase in the VSWC with soil depth and only a slightly higher VSWC at a soil depth of 20 and 30 cm than in the first survey at the start of the rainy season. The result obtained from the 400 MHz was slightly higher than those from the gravimetric. From the interpolated VSWC contour maps (Figure 7), the pattern was quite different from that of the first survey period. For the 400 MHz GPR analysis, the VSWC estimates were high in the western part of the study site area (40%) in a north-south orientation and sharply decreased in the eastern part (~30%). For the 900 MHz GPR analysis, the VSWC estimates were higher than in the first period (early rainy season) but still lower than those obtained from the gravimetric and 400 MHz GPR analyses, but the VSWC pattern was dissimilar to that obtained by the 400 MHz GPR analysis.

Table 2 VSWC estimations

Survey period	Soil depth (cm)	Gravimetric	%VSWC	
			400 MHz GPR[a)]	900 MHz GPR[a)]
		Range (Average)	Range (Average)	Range (Average)
Early rainy (29th Jul. 2014)	10	28.9–33.0 (30.3)	18.26–39.8 (31.0)	12.8–19.7 (15.8)
	20	25.3–35.1 (29.6)		
	30	23.7–34.5 (30.1)		
Rainy (23rd Nov. 2014)	10	26.5–34.2 (30.3)	27.0–42.0 (34.8)	16.5–19.1 (18.0)
	20	26.8–34.4 (31.4)		
	30	26.3–38.0 (31.5)		
Winter, dry (10th Feb. 2015)	10	6.75–15.5 (10.6)	15.0–23.5 (19.5)	13.7–17.9 (15.6)
	20	11.0–18.7 (13.5)		
	30	12.0–21.4 (15.4)		

[a)] The GPR results are not specified at any depth.

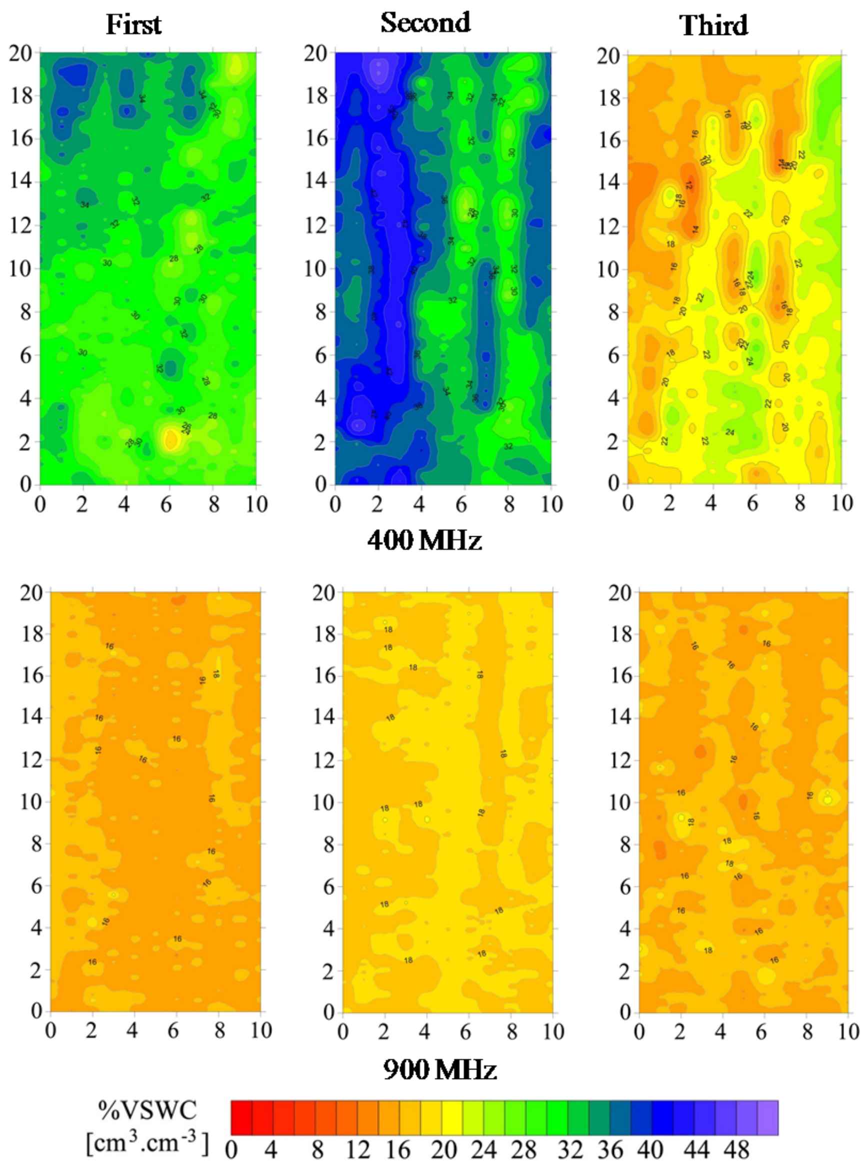


Figure 7 Contour maps of the VSWC of the study site derived from the (Top) 400 MHz GPR and (Bottom) 900 MHz GPR survey in the (Left) early rainy season on 29th July 2014, (Middle) late rainy season on 23rd November 2014 and (Right) dry or winter season on 10th February 2015.

The third survey was performed in the dry season (winter; 10th February 2015), when a lower VSWC was expected than in the two previous periods (rainy season). Indeed, no rainfall was recorded for the 1-month period prior to the survey. The VSWC estimates from the gravimetric analysis were indeed lower than in the other two periods in the rainy season and showed a clear tendency for the VSWC to increase with increasing soil depth. With respect to the 400 MHz GPR, the VSWC was higher than the gravimetric analysis but lower than that in the other two rainy seasons. Across the study site the VSWC values were low in the north-west part of the study site (16–17%) and high at the eastern part (24%). For the 900 MHz GPR derived results, the VSWC was slightly lower than the 400 MHz GPR analysis and less than in the previous two rainy season surveys, but still lower than that the gravimetric analyses. The VSWC pattern across the study field was not clear and dissimilar to that from the 400 MHz GPR analysis.

Discussion

1) Validation of the GPR method

The VSWC estimates from the GPR methods were compared at the same nine soil sampling sites with those derived from the gravimetric analysis of these soil samples, each at three different depths (10, 20 and 30 cm), by linear regression.

1.1) Early rainy season (29th July 2014)

When the GPR sends EMW into the subsurface, the wave passes through the whole medium and so comparisons between the GPR and gravimetric estimates of the VSWC should be made at an average depth rather than at a specific depth. For the 400 MHz GPR analysis, the VSWC estimates only showed a moderate positive correlation (about 0.732) at an average soil depth of 10 cm, with the deeper depths having no correlation (Figure 8). This is in good agreement with the influent depth of 8 cm.

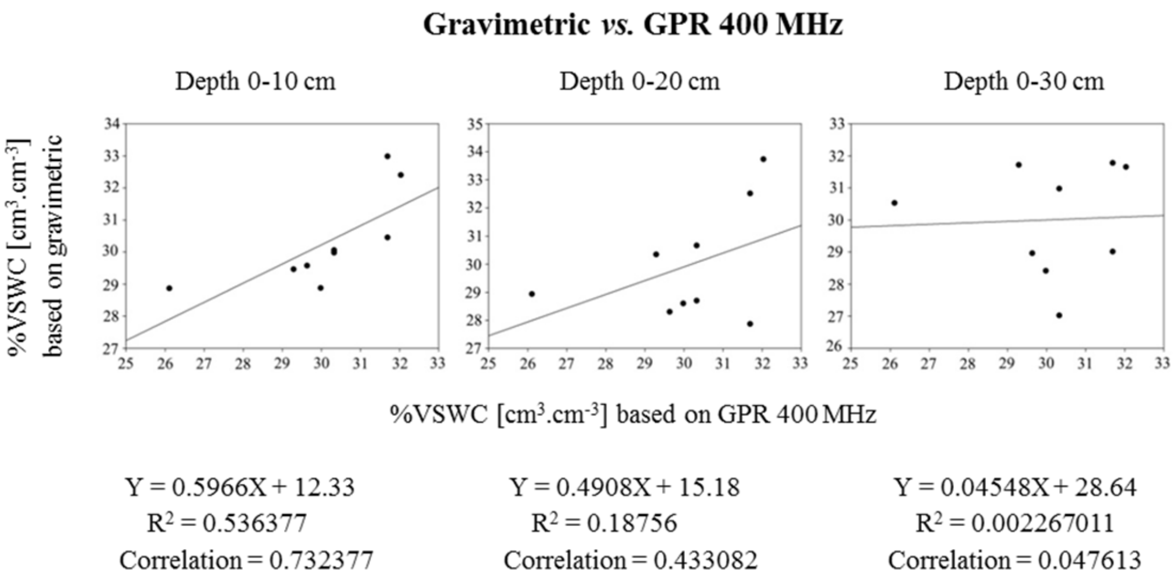


Figure 8 Relationship between the VSWC estimates derived from the gravimetric analysis in the early rainy season (29th July 2014) with the 400 MHz GPR for an average soil depth of 10 cm (Left), 20 cm (Middle) and 30 cm (Right).

In the validation of the GPR method to determine the VSWC in this study, the 900 MHz data were not included in the analysis due to its underestimation of VSWC. The underestimated VSWC results of the 900 MHz GPR may arise from the wrong antenna offset distance with the interference of air and ground waves. The superposition of the air and ground waves causes the air and ground waves to appear later and earlier, respectively, than they should [4]. So it gave a lower time difference input to Eq. 2 and so a lower VSWC estimation. Another reason is the influent depth is too shallow (just about 4 cm) to penetrate a sufficiently large soil sample. So, the results from the 900 MHz GPR analysis do not correlate with the gravimetric method in this study.

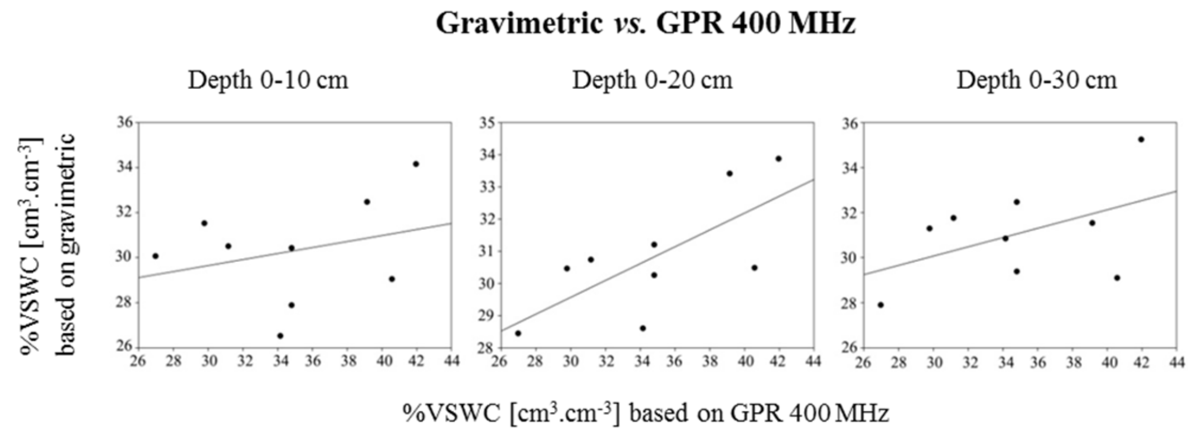
1.2) Late rainy season (23rd November 2014)

The VSWC estimates derived from the 400 MHz GPR survey at 20 cm depth had a moderate positive correlation (about 0.7) with those from the gravimetric analysis, but not at 10 or 30 cm (Figure 9). This does not accord with the influent depth of about 8 cm or with the results of the first survey in the early rainy season that had the best positive correlation at a 10 cm soil depth.

1.3) Dry (winter) season (10th February 2015)

With respect to the 400 MHz GPR, a reasonable positive correlation (about 0.7) was found with the gravimetric results at all three soil depths, with the strongest correlation at a 20 cm soil depth (Figure 10). Again, this is not in accord with the influent depth of about 8 cm.

Thus, in all three surveyed time periods, the VSWC estimates derived from 400 MHz GPR analysis had different relationships with the gravimetric analysis at each soil depth. Table 3 shows the correlation value and the percentage of root mean square error (RMSE) of all the results. However, the limitation of experiment made the soil samples to be disturbed on collection and so results to a loose compaction. It should be borne in mind that the disturbed soil samples would affect the evaluation of their density so the VSWC estimated from the gravimetric water content would also be moderately incorrect.

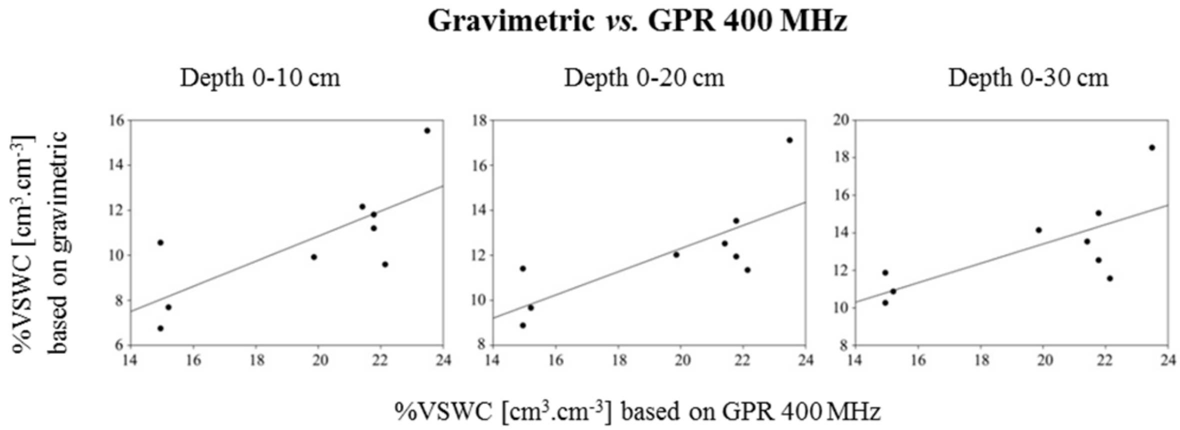


Y = 0.1336X + 25.64
R^2 = 0.084726
Correlation = 0.291077

Y = 0.2619X + 21.71
R^2 = 0.510925
Correlation = 0.714790

Y = 0.2057X + 23.9
R^2 = 0.232723
Correlation = 0.482414

Figure 9 Relationship between the VSWC estimates derived from the gravimetric analysis in the late rainy season (23rd November 2014) with the 400 MHz GPR for an average soil depth of 10 cm (Left), 20 cm (Middle) and 30 cm (Right).



Y = 0.5574X – 0.2977
R^2 = 0.565049
Correlation = 0.751697

Y = 0.5148X + 2.002
R^2 = 0.575682
Correlation = 0.758737

Y = 0.5164X + 3.075
R^2 = 0.499249
Correlation = 0.706575

Figure 10 Relationship between the VSWC estimates derived from the gravimetric analysis in the dry (winter) season (10th February 2015) with the 400 MHz GPR for an average soil depth of 10 cm (Left), 20 cm (Middle) and 30 cm (Right).

Table 3 Correlation and RMSE of the VSWC estimates derived from the gravimetric analysis with 400 MHz GPR analysis

Survey date	Soil depth (cm)	400 MHz GPR[a)]	
		%RMSE	Correlation
Early rainy (20th Jul 2014)	10	**1.173**	**0.732377**
	20	1.936	0.433082
	30	2.284	0.047613
Late rainy (23rd Nov 2014)	10	6.468	0.291077
	20	**5.451**	**0.714790**
	30	5.617	0.482414
Dry (winter) (10th Feb 2015)	10	9.190	0.751697
	20	7.768	**0.758737**
	30	**6.770**	0.706575

[a)] The GPR is compared with the gravimetric results at an average depth.
[b)] Bold values represent the best value for each survey date.

From table 3, the VSWC estimated from the 400 MHz GPR analysis at the start of the rainy season had the highest correlation and the lowest RMSE at an average soil depth of 10 cm, whereas in the late rainy season and dry season it was best correlated at a 20-cm soil depth, but a good correlation was observed at all three depths in the dry season. Accordingly, the 400 MHz GPR gave reasonable VSWC estimates at a soil depth of 10-20 cm in wet conditions, and additionally become reliable at 30 cm in dry conditions. This is due to the amount of moisture (e.g. rainfall) in the soil that affects the propagation of the EMW. In principle, aside from the dielectric permittivity, another significant variable of the soil media that effects signal attenuation (i.e. energy) of the EMW is the electrical conductivity, especially for high frequency EMW. The soil water content has many free ions that elevates the electric conductivity of wet soil to much higher levels than in dry soil, and so results in a greater attenuation of EMW. So, the drier soil conditions in the dry (winter) season accounts for the ability to determine the VSWC in the deeper soil depths.

Of interest is the best value (bold text in Table 3) for the 400 MHz GPR method is not at the same depth in the three different survey periods. The influence depth is proportional to the wavelength of the EMW in soil (i.e. the velocity), so a difference in the VSWC (proportional to ε_r or velocity of soil) will change the influence depth. This can be calculated from the WARR acquisition, which also gives the optimal Tx and Rx antenna offset. The survey in the late rainy season and dry season used the offset and influence depth data from the WARR analysis in the first survey (early rainy period), and so it was assumed these would not be change. This might help explain why the highest correlation between the VSWC values obtained from the GPR and gravimetric analyses were at different depths in the subsequent late rainy and dry seasons. Thus, the same configurations cannot be used in different sites or time periods, but rather the WARR acquisition must be performed at every different site and time period to obtain an appropriate offset and influent depth. Accordingly, the GPR analysis in the early rainy season is in strong accordance with the influent depth and had a low RMSE. Thus, the sledge should be modified to be able to change the offset.

In addition to changes in the soil electric conductivity due to rainfall, the soil texture is significant to GPR survey. The soil texture of the study area was loamy with a large proportion of silt and clay, which is not very suitable for GPR surveying [10] because the pore water increases the electric conductivity of the soil and causes a greater attenuation of the EMW. So, the soil texture differentially affected all three surveys.

2) Temporal variation in the VSWC

The GPR estimated VSWC values are illustrated as a contour map in Figure 7. At the start of the rainy season (first survey) the VSWC ranged from 18.2–39.7 (average 31.0) with the highest VSWC in the north-west corner of the study field. The later time points were surveyed with the same GP configuration (Tx and Rx offset distance and influent depth) to determine the changing of VSWC with time. At the end of the rainy season (second survey), a higher VSWC was found than at the start of the rainy season, ranging from 24.7–48.5% (average 36.3%) with most of the study area being >40% and with lower VSWC levels (25–30%) in the eastern part of the study area (30–32%) than in the western part (37-42%), both in a north-south orientation. For the third survey in the dry season, where there had been no rainfall for one month prior to the survey, the lowest VSWC was observed, ranging from 10.8–27.9% (average 19.6%). The east and northeastern parts of the study area had medium water content (22–24%) and the driest area was found at the north-west part (12–14%). It is clearly seen that the 400 MHz GPR derived VSWC changed in accord with season and rainfall, suggesting that the 400 MHz GPR method can respond to changes in the VSWC with time.

For the 900 MHz GPR analysis of the VSWC increased from 12.8–19.7% (average 15.8%) at the start of the rainy season to 15.5–22.3% (average 18. 0%) at the end of the rainy season and then decreased to 12.4–21.6% (average 16.1%) in the dry season. All these VSWC estimates were lower than those obtained using the gravimetric method and showed different VSWC distributions across the study field than those derived from the 400 MHz GPR analysis. Indeed, the results from the 900 MHz GPR analysis do not accord with the gravimetric method. Therefore, the 900 MHz GPR approach cannot be claimed to detect the variation of VSWC with time in this study.

Conclusion

Determination of the VSWC in loamy soil by the 400 and 900 MHz GPR ground wave fixed-offset technique was evaluated at a field scale at the CLNR, Chulalongkorn University, Saraburi province. This GPR method was found to be somewhat appropriate for estimating the VSWC due to the ease of data acquisition and processing as long as the antenna offset distance and influence depth were set by WARR analysis at each site and survey time. The 400 MHz GPR determination of the VSWC showed a high correlation with the standard gravimetric method under dry conditions (VSWC of 10–15%) at a soil depth of 10–30 cm. Under wet conditions (VSWC of ~30%), the result was reasonable at a soil depth of 10–20 cm. In contrast, the VSWC values obtained from the 900 MHz GPR were not related to those from the gravimetric method under all conditions, although the results were slightly improved under dry soil conditions.

The use of the 400 MHz GPR, but not the 900 HMz GPR, can effectively determine the VSWC at a soil depth of 10–20 cm. This limited depth is probably due to the high proportion of clay and silt in the soil that limits penetration of the GPR signal. This technique can be used in many types of soils but with different GPR frequencies and offset distances; but requires a specialist for operation and data processing. However, this method is worthy of further study to evaluate its effectiveness at a larger scale in helping to determine the VSWC in planning and managing agricultural fields.

The major limitation in this research was the sampling of disturbed soil. The gravimetric method was used as the reference for comparison, but required an accurate assessment of the bulk soil density, which would have been compromised by the sampling strategy.

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